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Erosion of Sediment and Organic Carbon from the Kara Sea Coast

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Abstract

We have estimated the erosion of sediment and organic carbon input from the Kara Sea coast based on extensive mapping, geologic and cryolithologic investigations of coastal zone and seafloor sediments, and revision of previously published data. The amount of coastal sediment eroded into the Kara Sea was determined to be approximately 35 million tons. Twenty-seven million tons are attributed to solid material, 7.6 million to thawed ground ice, 0.4 million to organic carbon, and 0.3 million to soluble salts. The estimate of organic carbon input presented herein is 2.5-fold less than previously published elsewhere. The majority of organic carbon in marine clayey deposits was found to be present in an adsorbed form. Its quantity corresponds to the content of clay particles in Pleistocene sediments. Organic carbon content in clay marine sediments remains unchanged during freeze-thaw processes, indicating that this form of carbon is stable unless thermoerosion is taking place.

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Introduction

Estimation of organic carbon budget in the Arctic seas has become an important topic under recent concerns of global warming (Petrova, 2001; Brown and Jorgenson, 2002; Grigoriev and Rachold, 2003; Rachold et al., 2000). Organic carbon from solid sediments is an important source of nutrition for sea biota in coastal zones (Lisitsin, 1994). Romankevich and Vetrov (2001) published a review of organic carbon cycles in the Arctic seas of Russia. Several studies have produced estimated values of organic carbon input from coastal erosion into the Arctic basin (Kosheleva and Yashin, 1999; Stein and Macdonald, 2003). In addition, Kholodov et al. (2003) conducted regional investigations of organic carbon content (OCC) in fine-grained sediments of the Laptev Sea and East Siberian Sea. Previous estimates of organic carbon input due to coastal erosion in the western sector of the Russian Arctic should be treated with caution, as they were based on few sampling locations and therefore provide limited ground truth data for regional estimates. Furthermore, the main sources of OCC data in these studies were obtained from engineering-geological investigations. Such investigations estimate the total organic matter based on a dry combustion method, in which samples are heated in an oven chamber to 950°C (Trofimov et al., 1975). The remaining product (the ash) is considered to be "true organic content." However, this method is known to overestimate organic content, because the extreme temperature may also result in the combustion of mineral soil.

The main goals of this research were to estimate the characteristic changes in coastline position and to calculate the annual mass-balance of sedimentation, including the amount of organic carbon input into the Kara Sea. Using our new field data we evaluate the amount, spatial patterns, form, and stability of organic carbon in Pleistocene and Holocene sediments of the Kara Sea coast.

Environmental Factors Responsible for Coastal Erosion

REGIONAL CLIMATIC CONDITIONS

The Kara Sea is located in the western sector of the Russian Arctic. Pronounced increase in climate severity from west to east is characteristic for the western sector of the Russian Arctic in general and is particularly relevant to the Kara Sea region. Mean annual air temperature decreases from −6.8°C in Amderma, to −8.0°C in Marresale and to −10.9°C in Gyda (Gydanskiy Poluostrov). The lowest mean annual temperature occurs in the most eastern part of the coast and is around −11.2°C in Dikson (Northwestern Taymyr).

Analyses of meteorological data from polar stations (Vasiliev, 2005; Vasiliev et al., 2006) have shown that oscillations in air temperature in time have occurred simultaneously in the entire Kara Sea coast region. From the year 1940 until 1970, a general decrease in the mean annual air temperature was observed. However, from 1970 until 1998, an increasing trend in the mean annual air temperature was observed.

The duration of ice free periods is an important climatic parameter, as coastal erosion cannot occur while the sea is covered with ice. However, very few coastal meteorological stations have long-term data on the duration of ice-free periods. One of the longest records available is from the Marresale Polar Station, which has been monitoring ice conditions since 1942. The average duration of an ice-free period is approximately 70 days. The longest recorded ice-free period is 126 days and occurred in 1942 and 1995. The shortest ice-free period was observed in 1978, when ice did not melt completely until the end of the summer (Vasiliev et al., 2006). The duration of ice-free periods is highly correlated with air temperature oscillations. As mean annual temperatures decreased between 1940 and 1970, a decrease in duration of the ice-free period was observed. Likewise, as mean annual temper-

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atures began to increase from 1970 until 1998, a general increase in duration of ice-free periods was observed.

The thermoabrasive coasts of Kara Sea are frozen for the majority of the year. Intensive erosion occurs only during the warm season, when sea ice is far away from the shore. In addition to temperature, there are other factors responsible for the destruction of sea ice; wind speed and waves are the primary factors. It has been speculated that the erosion of coasts occurs mainly under conditions of storm waves in combination with fetches. However, quantitative estimations of the storms' role in erosive processes of the Kara Sea coasts are not available. Analysis of meteorological data for the period 1996–2004 has shown that there are two maximums in the distribution of the wind speed. One is in a range from 2 to 5 m s^{-1} and the other is from 5 to 10 m s^{-1}. In general, their reiterations are very close to each other. Occurrence of wind with a speed of more than 10 m s^{-1} (storm winds) was found to be less than 5% of total distribution, with an exception of 1998, when it had reached 18% (Vasiliev et al., 2006).

In fact, after big storms wave-cut niches can be seen everywhere and large blocks of frozen ground can be expected to fall into the sea. Monitoring data show that the majority of waves have a height of 0.5 m and their effect on coastal erosion is relatively high. The occurrence of waves with a speed less than 10 m s^{-1} reaches up to 60–65%.

GEOLOGICAL AND GEOMORPHOLOGICAL CONDITIONS

The coasts east of Baydaratskaya Guba, Poluostrov Yamal, Gydanskiy Poluostrov, Tazovskiy Poluostrov, and the Northwestern Taymyr are mainly represented by Pleistocene and Holocene sandy-clay sediments of marine genesis. They are characterized by preserved saline content. The sediments of continental genesis are rare and can be found only in the upper parts of the coastal profiles where they play a secondary role. Relief of the coastal zone is represented by eroded surfaces of ancient marine and lacustrine-marine terraces up to 50–80 m high, and by contemporary deltas and laidas up to 0.5–3.5 m a.s.l. Some terraces are composed of bedrocks with bases composed of parent material.

During the Pleistocene, periods of warming alternated with periods of cooling. Large ice sheets in the Arctic were developing and degrading (Svendsen et al., 1999; Forman et al., 1999). Sea transgressions were penetrating far inland. This is supported by the observation of wide distribution of a thick layer of marine Pleistocene sediments (Lazukov, 1972; Danilov, 1978a, 1978b). Sea regressions were drying the continental shelf (Stein et al., 2002), which became exposed to severe cold conditions causing it to freeze to a great depth. The ground ice (particularly, massive tabular ground ice) of different geneses were formed (Dubikov, 2002; Shpolyanskaya et al., 2002). The last sea level rise created conditions for almost complete permafrost degradation of the shelf. Only in coastal zones was permafrost preserved. The modern shape of the Kara Sea coastal line was formed only around 5000–6000 years ago (Biryukov and Sovershaev, 1998). The genesis and lithological composition of Quaternary sediments, as well as the age of main geomorphological coastal levels, are well known for the region. In this paper we adapted stratigraphic schemes developed by Baulin et al. (1967), Lazukov (1972), Danilov (1978b), Forman et al. (1999), and Dubikov (2002).

PERMAFROST CONDITIONS

The contemporary coastal zone of the Kara Sea is underlined by continuous low-temperature permafrost. Mean annual ground temperature varies from −2.0 to −10°C and permafrost thickness varies from 100 to 300 m or more. Ground ice is absent in parent bedrocks. The amount of ice inclusions in sand, silt, and clay from sea coast sediments depends on the sedimentation environment and cryogenic conditions. In marine sediments, which were exposed to freezing following the drop in sea level (so-called "epigenetic type"), the total ground ice content varies in a wide range from 20 to 40% (Kanevskiy et al., 2005).

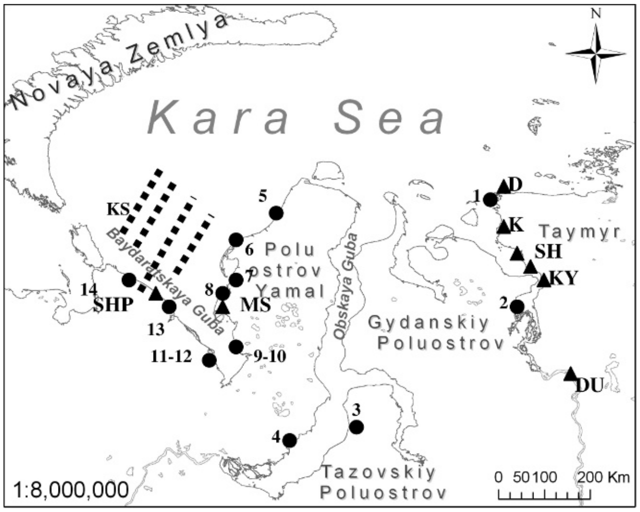

FIGURE 1. Black circles—location of the study sites: 1 to 14—coastal dynamics monitoring sites (more details in Table 1). Black triangles and block letters—locations of the exposures where samples for organic carbon content were collected. SHP—Point Shpindlera, DU—Dudinka, KY—Krasniy Yar, SH—Shaytansky, SK—Sopochnaya Karga, D—Dikson, K—Krestyanka, MS—Marresale, KS—Kara Sea (more details in Table 2). Black dotted lines—cross sections in Kara Sea where Kara Sea bottom sediments were sampled. Latitude 70°00′–72°00′N, longitude 60°00′–66°00′E.

Sandy-clay sediments of alluvial, deluvial, and lacustrine genesis, which were freezing simultaneously with sedimentation ("syngenetic type"), form the upper parts of the ancient terraces and contemporary accumulative levels. Total ice content in such sediments is higher than in the underlying epigenetic section and can reach up to 60% and more. Sections with very high ice content, referred to in literature as "ice complex," contain syncryogenic ice wedges up to 5 m thick.

Tabular ground ice is found in coastal exposures of the Kara Sea at different levels. Spatial distribution of tabular ice bodies is very uneven. They are characterized by different inclinations relative to the parent material. Thickness of the ice varies from several meters up to 50 m; its length varies from 10 m up to several kilometers (Streletskaya et al., 2003). The majority of geological sections with tabular ground ice is confined to the areas of Pleistocene marine transgressions, characteristic of prolonged marine and glacial-marine sedimentation (Poluostrov Yamal, Gydanskiy Poluostrov, and the Northwestern Taymyr) (Shpolanskaya and Streletskaya, 2004). Role of ground ice in sediments exposed to coastal erosion in Arctic is still under discussion (Hequette and Barnes, 1990).

Methods

FIELD PROCEDURES

The Kara sea thermoabrasive coasts and seafloor sediments were under complex investigation (Fig. 1). Lithological composi-

TABLE 1

Characteristic retreat rates of the Kara Sea coasts averaged for the last 40 years (after Vasiliev et al., 2006). Nos. 1–14: coastal dynamics monitoring site numbers in Figure 1 (black circles).

#	Location	Height of coastal exposures (m a.s.l.)	Lithology	Coast Retreat Rate (m yr^{-1})			Sources
				Max.	Min.	Average	
1	Northwestern Taymyr	10–40	Clay and sand underlying by parent bedrocks	0.4	0.2		Romanenko (1998)
2	Gydanskiy Poluostrov	20–40	Clay with layers of sand	0.4	0.2		Author research results
3	Tazovskiy Poluostrov	10–30	Clay with layers of sand			0.7	Author research results
4	Obskaya Guba, Saleta	8–10	Sand	0.7		0.33	Medkova (2002)
5	Northwestern Poluostrov Yamal	8	Sand with layers of clay			0.8	Voskresenskii and Sovershaev (1998)
6	Western Poluostrov Yamal	10–25	Clay with layers of sand, sand	4.5	0.4		Solomatin (1992)
				2.0			Kamalov et al. (2002)
				3.0	0.5	1.4	Author research results
7	Western Poluostrov Yamal	40	Sand	1.0	0.5		Voskresenskii and Sovershaev (1998)
8	Western Poluostrov Yamal, Marresale	10–30	Clay, loam, sand			1.8	Troitskii and Kulakov (1976)
						2.5	Firsov et al. (2002)
				1.9	1.0		Kritsuk and Dubrovin (2000)
				1.8	1.0	1.4	Shur et al. (1984)
				3.3	0.5	1.7	Vasiliev et al. (2001)
9	Baydaratskaya Guba, southeastern coast	10–25	Sand underlying by loam	0.9	0.05	0.4–0.5	Dubikov (1997)
10	Baydaratskaya Guba, southeastern coast	6–10	Sand, peat	0.7	0.3		Dubikov (1997)
11	Baydaratskaya Guba, southwestern coast	5–17	Sand with layers of loam and sandy loam	3.5	1.0	1.7	Dubikov (1997)
12	Baydaratskaya Guba, southwestern coast	2–3	Sand, sandy loam	0.6	0.2	0.4	Dubikov (1997)
13	Baydaratskaya Guba, western coast, Novyy Dom	30–50	Clay, sand	2.0	0.9	1.2	Kizyakov and Perednya (2003)
14	Baydaratskaya Guba, western coast, Amderma	10–20	Clay			1.1	Kizyakov (2005)

tion of the deposits and the contents of salts, ice, and organic carbon were studied in the collected samples. The age and genesis of sediments were also analyzed.

Geological profiles in Kharasavei, Marresale (Western Poluostrov Yamal), Shpindlera (western coast of Baydaratskaya Guba), and Sopochnaya Karga (West Taymyr) were chosen to be representative of thermoabrasive coasts of western and eastern sector of the Kara Sea, respectively. Starting from 1978, the field work at the selected key sites was aimed at a detailed study of their geological and geocryological structure. Lithological composition of the deposits and the contents of salts, ice, and organic carbon were studied in the collected samples.

Observational sections with benchmarks were installed at the key sites perpendicular to the coastline. The distance between sections varied from 20 to 50 m. The length of the shores with installed observational sections varied from 1 to 4.5 km at different key sites.

Measurements of the exact position of the upper edge of shore cliffs have been performed every year, at the end of the warm season. As coastal geosystems are generally balanced, the retreat rate of cliff edges approximately corresponds to the coastal retreat rate.

Starting from 2001, highly precise geodetic measurements of the relief of terrestrial parts of the key sites have been performed with the use of an electronic tachymeter (DTM-350; error of measurements $\leq$0.1 m). The positions of the shoreline (with due account for tidal cycles) and the upper edge and foot of the cliff have been determined with the use of GPS technique (GeoExplorer 3). In addition to our field data, a large amount of previously published data on costal erosion was analyzed (Table 1).

Samples for OCC were taken from more than 30 representative coastal exposures of Pleistocene and Holocene sediments with an elevation ranging from 1 to 80 m a.s.l. Twelve samples were obtained from Middle Pleistocene marine and glacial-marine clay sediments in the western coast of Baydaratskaya Guba (Shpindlera). Seventy-four samples were obtained from the thermoabrasive coasts with a height of 12–40 m composed of marine and alluvial Late Pleistocene (m III$^{1-3}$; a III^{4}–IV) and Holocene (m, am IV) sediments in Western Poluostrov Yamal, Marresale. Seventy-four samples were collected in Northwestern and West Taymyr coasts from thermoabrasive coasts with a height of 12–80 m composed of marine, glacial-marine, lacustrine, alluvial, and deluvial sediments of Pleistocene and Holocene age: m III$^{1-3}$; l III$^{3-4}$; d, a III^{4}–IV (Dudinka, Krasniy Yar, Shaytansky, Sopochnaya Karga, Dikson, Krestyanka).

Seafloor sediments were extensively mapped and sampled in the region 70°00′–72°00′N/60°00′–66°00′E (Fig. 1). Seafloor sediments were sampled for mineralogical analysis from depths of 13 to 213 m by 43 gravity corers in the region. About 125 samples were taken at depths from 0.0 to 3.0 m from the bottom surface. OCC was estimated in 96 samples.

ESTIMATION OF SEDIMENT MASS BALANCE

The entire coastline of the Kara Sea was subdivided into homogeneous segments using Arctic Coasts of Russia GIS database and field observations. The length, average height, and retreat rate of each segment was calculated for further calculation of the annual volume of material coming to the sea.

Balance of the sediment (BS) input for each coastal segment of the Kara Sea was calculated by following:

$$\mathrm{BS} = \mathrm{L} \times \mathrm{H} \times \mathrm{R} \times \mathrm{BD} \left(\text{millions of tons yr}^{-1}\right), \qquad (1)$$

where L = length of coastal segment (m), H = average height of coast (m), R = retreat rate in the (m yr^{-1}), and BD = bulk density (kg m^{-3}). For computational purposes it was assumed that density of frozen clay is 1900 kg m^{-3}, and sand is 1700 kg m^{-3}.

ANALYSIS OF ORGANIC CARBON CONTENT

Analysis of OCC in 226 collected samples was conducted by Department of Lithology and Geochemistry of All-Russian Research Institute for Geology and Mineral Resources of the World Ocean (VNIIOceangeologiya) in St. Petersburg, Russia. The determination of OCC was performed according to methodology proposed by Knop (Russia) and is based on "wet combustion." The wet combustion method is based on carbon oxidation under the heating by dichromate solution with sulfuric acid:

$$2CrO_3 + 3H_2SO_4 + 3C = 3CO_2 + Cr_2(SO_4)_3 + 3H_2 \quad (2)$$

Carbon dioxide generated due to organic carbon separation is collected and weighed. Determination occurs by means of a regular device designed to test CO_2 content. Analysis is conducted in two stages. The first stage eliminates carbonaceous carbon. During the second stage, CO_2 from the organic component is released by a reaction with oxidant (chromic anhydride) and weighed (Danyushevskaya, 1990).

Collected field and previously published data (Streletskaya et al., 2008) was used to estimate an average amount of organic carbon for each coastal segment (CS) stored in sediments of different genesis, age and cryogenic history as follows:

$$CS = \text{average OCC } (\%\ \text{weight}) \times BS \quad (3)$$

Based on the ice content and dissolved salts data, the portion of melted ice in the total volume of thawed material and amount of salts were also estimated for every coastal segment.

Results of mapping surveys of the coastal lines, complex investigation of texture, ice content, soluble salts composition, OCC in coastal sediments, and data on retreat rates allowed us to estimate the mass-balance of material coming to the Kara Sea due to coastal erosion. Total balance of annual volume of material including organic carbon stocks coming to the sea was calculated as a sum of the balances of every coastal segment.

Results and Discussion

COASTAL GEOLOGY, GEOMORPHOLOGY, AND CRYOSTRATIGRAPHY

A series of coastal exposures on the Kara Sea was investigated during field seasons between 2004 and 2007. Most of the sites were subject to extensive sampling for organic carbon content.

The key study area Marresale is located on third and second marine terraces, with coastal steeps up to 20–30 m in height and periodically flooded lowlands. Modern syncryogenic alluvial-marine sediments (amIV) are formed in the mouth of the Marre-Yakha River, and littoral sediments (mIV) are formed in low periodically flooded laidas around 20 km south from Marresale Polar Station. Two complexes of Pleistocene deposits were determined in the coastal exposures near Marresale. The upper part of the profile is represented by syn- and epigenetic continental Late Pleistocene and Holocene sand and loamy-sand deposits (III^4–IV) of alluvial, bog, lacustrine, and eolian genesis. Ice wedges of 4–6 m thickness are common. The lower complex is represented by epicryogenic Late Pleistocene marine saline clays and loams with deformed lenses of sand ($mIII^{1-3}$). Lenses of tabular ground ice from 2 to 6 m thick were documented (Streletskaya et al., 2006a). The cryogenic features and geochemical composition of the sediments revealed that the epicryogenic marine sediments in some areas had partially thawed under thermokarst lake development and refroze again after the drainage of the lakes. The ice structure does not inherit sedimentation cleavage, and marine deposits are desalinated; however, the composition of soluble salt ions is characteristic of marine type sedimentation (Kanevskiy et al., 2005). The processes of soil and peat formation are typical for low accumulative surfaces. On surfaces periodically flooded by tides and waves, organic carbon accumulates in a detritus form.

Two complexes of Pleistocene deposits were determined to exist in the coastal exposures near Sopochnaya Karga (West Taymyr). The upper part of the profiles (5–6 m depth) is syncryogenic and consists primarily of loamy sand. Loamy sand has high organic and high ice content, including ice wedges. Its belt-shape cryogenic texture, high (up to 70%) ice content, and presence of massive syngenetic ice wedges permits the classification of this part of the profile as an ice complex (ds, a III^4–IV), which was formed in continental conditions. The lower part of the profile is represented by epicryogenic clayey marine sediments ($mIII^{1-3}$). Granulometric composition of the sediments is characteristic of aquatic sedimentation environments, in which particle precipitation occurs below the level of wave sorting. Clay sediments are saline (up to 0.5%) and diagnosed as marine.

COASTAL DYNAMICS

The total length of the Kara Sea coast is around 15,000 km according to the Arctic Coasts of Russia GIS database, which was developed under the umbrella of the Arctic Coastal Dynamic (ACD) project (Drozdov and Korostelev, 2003; Rachold et al., 2005). Most of the coastline is represented by low contemporary accumulative coasts (laidas) and parent bedrocks.

The total length of thermoabrasive coasts on Holocene–Pleistocene sediments with high ice content is around 2600 km. Although thermoabrasive coasts comprise only 17% of the entire Kara Sea coastline, their erosion is one of the major contributors of solid sedimentation, including organic carbon, to the Kara Sea basin.

Monitoring data on coastal dynamics from Marresale allows the establishment of a quantitative relationship between energy from sea waves and coastal erosion rates. These data show that the portion of storms in the total energy of sea waves is relatively low and usually is less than 10%. An exception occurred in 1995, when the portion of energy created by storm waves reached up to 20% (Vasiliev et al., 2001; Vasiliev, 2003, 2005).

The leading erosive factor of the Kara Sea coasts composed of sandy-clay sediments with a relatively small ice content is waves with height less than 1 m. Continuous impact of these waves on offshore slopes and cliff bases initiates a disturbance in an equilibrium coastal profile and develops destructive processes in the shore zone, which ultimately leads to coastal retreat. During warm seasons retreat rates of upper coastal edge and cliff can differ, but this difference becomes negligible in a long-term range. Therefore, ice content plays an important role in coastal retreat rate (Vasiliev et al., 2006). Thermodenudation can reach up to 0.4 m yr^{-1} if wave influence is eliminated. The average annual total coastal retreat was found to be 1.7 m yr^{-1}, so input of thermodenudation is less than 25%. Thermodenudation plays a more significant role in the erosion of coasts with higher ice content, being the main contributor to the retreat of the coasts represented by ice complex. Location of all sites where data are available is presented in Figure 1. Summary statistics on coastal retreat is presented in Table 1.

Analysis of the data shows that different researchers present varying results of coastal retreat measurements for the same areas. This can be explained by high spatial and temporal variability of coastal erosion in regions underlain by permafrost. Differences in methodology create another source of error, resulting in substantial differences in measurements from the same areas (Shur et al., 1984; Vasiliev, 2003). However, the amount of available data does allow for an estimation of retreat rates for characteristic coastal types. These rates are found to range from 0.8 to 2.0 m yr^{-1} for Kara Sea coasts. Coasts of the narrow gulfs such as Obskaya Guba have a retreat rate from 0.2 to 0.7 m yr^{-1}.

A special investigation was performed to evaluate the role of ground ice in sediments exposed to coastal erosion near Marresale during the year 2002. The study included investigation of the ice content in coastal sediments and parallel monitoring of the coastal retreat rate. Results showed that an increase in ice content from 25 to 45% correlated to increased total retreat rate of the upper coastal edge by a factor of 2 for the period between 1978 and 2002.

MINERALOGY OF COASTAL AND SEAFLOOR SEDIMENTS

Marine Pleistocene sediments of West Siberia and modern marine sediments of the Kara Sea have similar mineralogical associations, confirming a consistent supply of mineralogical sources during the entire Pleistocene period.

Dominant clayey minerals of polar seas are composed of hydromica and montmorillonite with a small amount of chlorite and kaolin (Danilov, 1978a). Kaolin is present in regions located in close proximity to the sedimentation sources, while montmorillonite is dominant in remote regions (Lapina and Belov, 1960). According to Lapina (1964), the dominant minerals in Arctic Ocean marine sediment fractions of less than 0.001 mm are hydromica of the illite type, rarer hydromuscovite, hydrobiotite, fine quartz with traces of beidellite, tiff, dolomite, and organic detritus. Our data and previously published materials (Baulin et al., 1967; Danilov, 1978b; Dubikov, 2002; Trofimov et al., 1975) show that clay content (particles size of <0.005 mm) in Middle Pleistocene marine sediments is more than 45%. Clay content in Late Pleistocene marine sediments is less than 30% (Streletskaya et al., 2006b).

Results of the mineralogical analysis of samples of Kara Sea bottom Holocene sediments show that clay particle content ranges from 40 to 73%, with a mean value of 51%.

The upper layer of bottom sediments of the Kara Sea is characterized by oxidized brownish silt and clay with some sand. Amount of sand in the sediments increases approaching the shore. Underlying reduced deposits have grayish, green, and olive color with black areas of hydrotroilite and orange areas of iron hydrates. Aleuric clays and pelite silts dominate the sediment clays.

VARIATION OF ORGANIC CARBON CONTENT IN COASTAL AND SEAFLOOR SEDIMENTS

As a rule, OCC in marine sands is less than in marine clay sediments of the coast and seafloor. For sands, rare inclusions of organic carbon in the form of thin layers of peat slime and organic detritus are typical. Such inclusions are very rare in marine clay sediments. At the same time, laboratory analyses show relatively high OCC in marine clay sediments (0.6–1.0%). Organic carbon is stored in these sediments in a different form. The amount of organic carbon stored increases with the number of clay particles (diameter size of <0.005 mm) present in sediments. This allows the assumption that organic carbon in clay sediments is stored in a scattered form, meaning that the particles are not visible, unlike detritus and peat remains. If this assumption is true, then OCC depends on the surface area of particles per volume, its initial concentration in sea water at the moment of sedimentation, and pH. Therefore, further analysis was focused on clay particle content as a marker of high concentration of organic carbon in marine sediments.

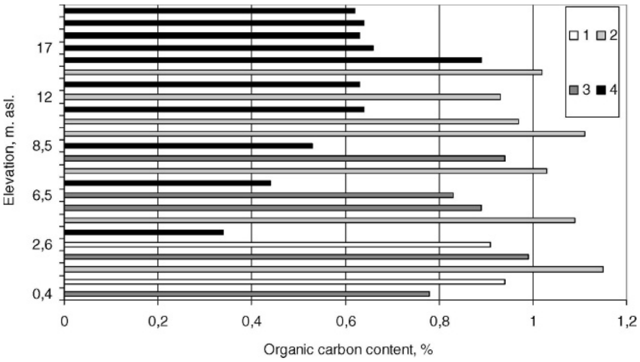

FIGURE 2. Vertical distribution of OCC in sandy-clay Middle and Late Pleistocene sediments of the Kara Sea coast. 1 to 3—Marresale location, 1—exposure 7/03, 2—exposure 2/03, 3—exposure 3/03, 4—Krasniy Yar location.

If OCC in clay marine sediments is presented in scattered form, it is expected that this form is relatively stable to changes of environment after sedimentation, and by extension, to processes of freezing and thawing. It was expected that maximum changes of organic carbon content due to freeze-thaw processes would be found in the upper sections of profiles. However, neither Middle Pleistocene (Krasniy Yar), nor Late Pleistocene (Marresale) clay sediments display such OCC changes with depth (Fig. 2). Moreover, OCC in sediments which have experienced freezing and thawing does not change compared to epicryogenic-bearing strata. This supports our assumption that the scattered form of organic carbon in clay marine sediments is stable.

Analysis of OCC from contemporary bottom sea sediments has shown that it ranges from 0.1 to 1.37%, with a mean of 0.92%.The upper section (0.0–0.2 m) has OCC ranging from 0.1 to 1.37%, with a mean value of 0.98%. Wide distribution of OCC values is determined by the presence of a sandy fraction in the upper part of the profile. Below, down to a depth of 0.7 m, the OCC decreases to 0.86%, and nears 0.93% at depths of 2.1–3.0 m. Summary statistics of OCC in Pleistocene deposits from the Kara Sea coast and seafloor are presented in Table 2.

In wide river deltas, organic carbon accumulates due to soil formation processes, presence of river vegetation, and peat accumulation. Organic carbon in alluvial-marine deposits is mostly present as organic detritus and the product of soil formation. Its content decreases with depth. For instance, at Marresale the OCC in surface sediments is more than 2.5%, while only 0.5% at a 2.0 m depth.

Conditions of organic carbon accumulation and transformation on surfaces periodically flooded by tides and waves have not yet been fully investigated. Analyses of a few samples show that, in sandy deposits of periodically flooded lowland surfaces, OCC is less than 0.1%. In sandy loam profiles some layers are enriched by organic detritus and peat slime. Here, oxidation and decomposi-

TABLE 2

Organic carbon content (OCC, %) in coastal and Holocene sea bottom sediments.

Location of exposures (black triangles and letters) and cross sections in Kara Sea (dotted line) in Figure 1	Age and genesis sediments*	Lithology	Average OCC (%)	Total no. of samples
Shpindlera (SHP)	m, gm II^{2-4}	Clay	0.7	12
Dudinka (DU), Krasniy Yar (KY), Shaytansky(SH)	m, gm II^{2-4}	Clay	0.6	23
Marresale (MS)	m III^{1-3}	Loam, clay	1.0	62
Sopochnaya Karga (SK)	m III^{1-3}	Loam, clay	0.9	14
Sopochnaya Karga (SK)	l III^{3-4}	Clay	0.7–1.5	3
Sopochnaya Karga (SK) Dikson (D), Krestyanka (K)	d, a III^{4}–IV	Silt	1.2	14
Marresale (MS)	a III^{4}–IV	Sand	0.25–035	6
Marresale (MS)	am IV	Sandy loam, sand	0.5–2.5	4
Marresale (MS)	m IV	Sand	<0.1	2
Kara Sea (KS)†	m IV	Clay	0.92	96

* Age and genesis sediments:
m, gm II^{2-4} (Middle Pleistocene marine and glacial-marine).
m III^{1-3} (Late Pleistocene marine).
l III^{3-4} (Late Pleistocene lacustrine).
d, a III^{4}–IV (Late Pleistocene and Holocene deluvial and alluvial).
am IV (Holocene alluvial-marine).
m IV (Holocene marine).

† Kara Sea bottom sediments were sampled in the region 70°00–72°00N/60°00–66°00E.

tion processes are active. In lacustrine clays, OCC is usually 0.7–1.0%, although in some cases it can be as high as 1.5%.

OCC in silt sediments of the ice complex in Northwestern Taymyr is 1.6–2.1%. Accumulation of organic carbon in the Sopochnaya Karga ice complex, in particular, does not differ from previously published data on regions of the northeast of Russia (Gubin, 2002). Detailed investigations of OCC in Pleistocene sediments of the Laptev Sea and East Siberian Sea coast indicate that almost all Pleistocene deposits in this region have a continental genesis (Kholodov et al., 2003). The broadest extent in this area has a silt ice complex and loamy sand of thermokarst lake deposits. Organic matter exists as detritus and molecular compounds (organic acids etc.) and is present in high content, reaching up to 5% in buried soils (Gubin, 2002). It is noted that prolonged thawing states of previously frozen ground substantially influence OCC (Kholodov et al., 2003). In secondary frozen sediments, OCC is always considerably less than in initial ones of the ice complex (Ostroumov et al., 2005). It is natural for relatively unstable forms of organic matter in sandy-clay sediments to be of a continental genesis.

MASS BALANCE OF SEDIMENT EROSION AND ORGANIC CARBON STOCKS

Total amount of material annually coming to the Kara Sea due to coastal erosion is about 35.0 million tons; 27.0 million tons is attributed to solid material, 7.6 million to thawed ground ice, 0.4 million to organic carbon, and 0.3 million to soluble salts (Fig. 3).

According to Mikhailov (1997), sediment runoff to the Kara Sea by the major rivers is equal to 27.3 million tons. Hence, input of solid material due to coastal erosion is almost equal to input from river sediment runoff. This confirms the assumption that coastal erosion plays an important role in the balance of solid material in the Kara Sea (Vasiliev et al., 2001).

Our results indicate that the organic carbon input to the Kara Sea due to coastal erosion is 2.5 times lower than the 1 million tons previously estimated by Romankevich and Vetrov (2001). This can be explained by two reasons: (1) the authors did not have enough data on coastal retreat rates and length of thermoabrasive coasts, leading to substantial overestimation of erosion volumes; and (2) the authors used coastal sediment OCC values calculated by the dry-combustion method, which is known to overestimate OCC. Together, these resulted in a 2.5-fold overestimation of organic carbon, which we have been able to more accurately determine.

Input of organic carbon by the major rivers to the Kara Sea is about 10 million tons (Gordeev et al., 1996). Hence, compared to input from river sediment runoff, organic carbon input from the coastal erosion is 25 times less, solid material input is roughly the same, and input from soluble salts is negligible, because of the sparse distribution in coastal sediments.

Conclusions

Complex geological and geocryological investigations show that thermoabrasive coasts are an important source of solid material and organic carbon to the Kara Sea. The total amount of

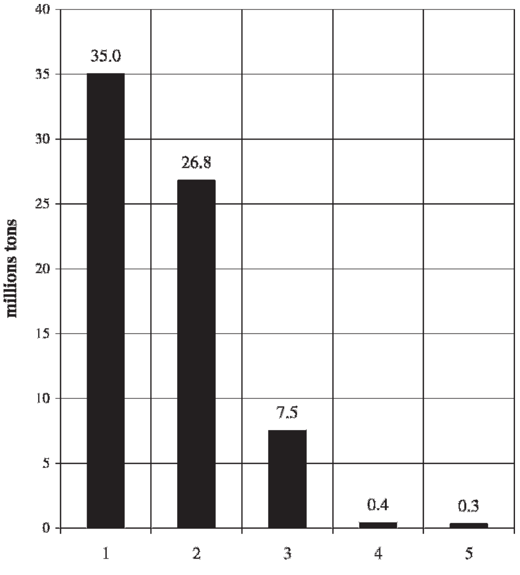

FIGURE 3. Input of the coastal erosion sediment to the Kara Sea (millions of tons per year). 1—Total; 2—Mineral Component (sand, silt, clay); 3—Ice (Water); 4—Organic Carbon; 5—Soluble Salts.

material, coming to the Kara Sea annually due to coastal erosion is about 35.0 million tons, including 0.4 million tons of organic carbon.

- OCC in modern sediments of the seafloor and those of Pleistocene marine coastal sediments confirm the existence of a common source of organic carbon input during the entire Pleistocene period.
- The average values of OCC in marine clay sediments of the seafloor are similar to that obtained from marine Pleistocene clays of the coasts.
- Organic carbon in clay marine Pleistocene–Holocene coastal sediments and contemporary sediments of the seafloor is present mainly in the adsorbed form.
- OCC in clay marine sediments does not change due to processes of thawing/freezing, which confirms that this form is stable throughout environmental changes.
- Distribution of OCC in sections of contemporary sediments of the Kara Sea shows an absence of decomposition features in organic matter at the post-sedimentation stage.

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References Cited

Baulin, V. V., Belopukhova, E. B., Dubikov, G. I., and Shmelev, L. M., 1967: *Georiologicheskie usloviya Zapadno-Sibirskoi nizmennosti [Geocryological Conditions of West Siberian Plain]*. Moscow: Nauka, 214 pp. (in Russian).

Brown, J., and Jorgenson, M. T., 2002: Carbon estimates from two Beaufort Sea key sites. Arctic Coastal Dynamics. Report of an International Workshop, Potsdam (Germany) 26–30 November 2001. *Reports on Polar and Marine Research*, 413: 25–27.

Biryukov, V. Y., and Sovershaev, V. A., 1998: Geomorfologiya dna Karskogo moray [Bottom geomorphology of Kara Sea]. *In* Solomatin, V. I., Sovershaev, V. A., and Mazurov, I. I. (eds.), *Dynamics of Russian Arctic Shores*. Moscow: Izdatelstvo MGU (MSU Press), 102–115 (in Russian).

Danilov, I. D., 1978a: *Polyarnyi litogenes [Polar Lithogenesis]*. Moscow: Nedra, 238 pp. (in Russian).

Danilov, I. D., 1978b: *Pleistotsen morskikh Subarkticheskikh ravnin [The Pleistocene of Marine Subarctic Plains]*. Moscow: Izdatelstvo MGU (MSU Press), 198 pp. (in Russian).

Danyushevskaya, A. I. (ed.), 1990: *Organicheskoe veshchestvo donnykh otlozhenii polyarnykh zon Mirivigo okeana [Organic Carbon in Bottom Sediments of World Ocean Zones]*. Leningrad: Nedra, 280 pp. (in Russian).

Drozdov, D. S., and Korostelev, Yu. V., 2003: Environmental maps of the Russian Arctic as a base for the segmentation of the coastline and the analyses of coastal dynamics. *In* Haeberli, W., and Brandova, D. (eds.), Extended abstracts. Reporting Current Research and New Information. 8th International Conference on Permafrost, Zurich, Switzerland, 20–25 July 2003, Glaciology and Geomorphodynamics Group, Geography Department, University of Zurich, Switzerland, 27–28.

Dubikov, G. I. (ed.), 1997: *Prirodnye usloviya Baidaratskoi guby. Osnovnye rezultaty issledovanii dlya stroitelstva podvodnogo perekhoda [Natural Condition of Baidarata Gulf. General Results of Investigation for Underwater Cross Construction]*. Moscow: GEOS, 432 pp. (in Russian).

Dubikov, G. I., 2002: *Sostav i kriodennoe stroenie merzlyh tolshch Zapadnoi Sibiri [Composition and Cryogenic Structure of Permafrost in West Siberia]*. Moscow: GEOS, 246 pp. (in Russian).

Firsov, Yu. G., Ivanov, M. V., Cherkashev, G. A., and Vanshtein, B. G., 2002: The dynamic coastline observation program for the Marre-Sale polar station, the Kara Sea [abstract]. *In* International Conference Extreme Phenomena in Cryosphere: Basic and Applied Aspects. 13–15 May 2002, Pushchino, Russia, 235–236.

Forman, S. L., Ingolfsson, O., Gataullin, V. N., Manley, W. F., and Lokrantz, H., 1999: Late Pleistocene stratigraphy of western Yamal Peninsula, Russia: new constraints on the configuration of the Eurasian ice sheet. *Geology*, 27: 807–810.

Golfarb, Yu. I., and Ezhova, A. B., 1990: Relict massive ground ice on Yugorsky Peninsula. *In* Shats, M. M., and Kuzmin, G. P. (eds.), *Voprosy razvitiya i osvoeniya merzlykh tolshch [Question of Evolution and Development of Permafrost]*. Yakutsk, 22–31 (in Russian).

Gordeev, V. V., Martin, J. M., Sidorov, I. S., and Sidorova, M. V., 1996: A reassessment of the Eurasia River input of water, sediments, major elements, and nutrients to the Arctic Ocean. *American Journal of Science*, 296: 664–691.

Grigoriev, M. N., and Rachold, V., 2003: The degradation of coastal permafrost and the organic carbon balance of the Laptev and East Siberian Seas. *In* Philips, M., Springman, S. M., and Arenson, L. U. (eds.), Proceedings of the 8th International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland. Rotterdam, A. A. Balkema Publishers, 1: 319–324.

Gubin, S. V., 2002: Pedogenesis is part of mechanism of formation of deposits in Late Pleistocene ice complex. *Kriosfera Zemli [Earth Cryosphere]*, VI(3): 82–91 (in Russian).

Hequette, A., and Barnes, P. W., 1990: Coastal retreat and shoreface profile variations in the Canadian Beaufort Sea. *Marine Geology*, 91: 113–132.

Kamalov, A. M., Ogorodov, S. A., and Arkhipov, V. V., 2002: Coastal dynamics in Western Yamal [abstract]. *In* International Conference Extreme Phenomena in Cryosphere: Basic and Applied Aspects. 13–15 May 2002, Pushchino, Russia, 233 pp.

Kanevskiy, M. Z., Streletskaya, I. D., and Vasiliev, A. A., 2005: Formation of cryogenic structure of Pleistocene sediments in Western Yamal. *Kriosfera Zemli [Earth Cryosphere]*, IX(3): 16–27 (in Russian).

Kholodov, A. L., Rivkina, E. M., Gilichinskii, D. A., Fedorov-Davydov, D. G., Gubin, S. V., Sorokovikov, V. F., Osrtoumov, V. E., and Maksimovich, S. V., 2003: Estimation of the organic carbon input into Arctic Ocean due to erosion of Laptev and East-Siberia seashore. *Kriosfera Zemli [Earth Cryosphere]*, VII(3): 3–12 (in Russian).

Kizyakov, A. I., 2005: *Dinamika termodenudatsionnykh protsessov v raionakh rasprostraneniya zalezhei plastovykh l'dov [Termodenudation Processes Dynamic in Massive Ground Ice Extend Area]*. Dissertation. Moscow: Izdatelstvo MGU (MSU Press), 26 pp. (in Russian).

Kizyakov, A. I., and Perednya, D. D., 2003: Destruction of coasts on the Yugorsky Peninsula and on Kolguev Island, Russia. *In* Haeberli, W., and Brandova, D. (eds.), Extended abstracts. Reporting Current Research and New Information. 8th International Conference on Permafrost, Zurich, Switzerland, 20–25 July 2003, Glaciology and Geomorphodynamics Group, Geography Department, University of Zurich, Switzerland, 79–80.

Kosheleva, V. A., and Yashin, D. S., 1999: *Donnye osadki Arkticheskikh morei [Bottom Deposits of Russian Arctic Seas]*. St. Petersburg: VNIIOkeangeologia, 286 pp. (in Russian).

Kritsuk, L. N., and Dubrovin, V. A., 2000: Potzemnye l'dy I kriogennye protsessy v raione Marre-Sale (Zapadnyi Yamal) [Underground ice and cryogenic processes in the Marresale area (Western Yamal)]. *In* Demyanova, I. A. (ed.), *Gidrogeologicheskie, inzhenerno-geologicheskie i geokriologicheskie issledovaniya [Hydrogeological, Engineering-Geological and Geocryological Survey]*. Moscow: Geoinformmark Press, 14–25 (in Russian).

Lapina, N. N., 1964: Material composition of fine bottom sediment of North Ocean. *In* Reports of International Geological Congress. Geology of bottom oceans and seas. XXII session. Moscow: Nauka Press, 122–130 (in Russian).

Lapina, N. N., and Belov, N. A., 1960: Osobennosti protsessa osadkoobrazovaniya v Severnom Ledovitom Okeane (Features of sedimentation processes in North Ocean). *In Sovremennye osadki morei i okeanov [Recent sediments of seas and oceans]*. Proceedings of conference 24–26 May, 1960. Moscow: Izdatelstvo Akademii Nauk [Academy of Sciences Press], 124–174 (in Russian).

Lazukov, G. I., 1972: *Antropogen severnoi poloviny Zapadnoi Sibiri (paleogeografiya) [Anthropogenesis of West Siberia Northern Part (Paleogeography)]*. Moscow: Izdatelstvo MGU (MSU Press), 250 pp. (in Russian).

Lisitsin, A. P., 1994: Ocean marginal filters. *Oceanology*, 34(5): 735–747 (in Russian).

Medkova, O. N., 2002: The geomorphology and coastal dynamics in the southern part of the Gulf of Ob [abstract]. *In* International Conference Extreme Phenomena in Cryosphere: Basic and Applied Aspects. 13–15 May 2002, Pushchino, Russia, 247–248.

Mikhailov, V. V., 1997: *Ustya rek Possii i sopredelnykh stran [River Mouths of Russian and Contiguous Countries: Past, Present and Future]*. Moscow: GEOS, 413 pp. (in Russian).

Ostroumov, V., Rachold, V., Vasiliev, A., and Sorokovikov, V., 2005: An application of a Markov-chain model of shore erosion for describing the dynamics of sediment flux. *Geo-Marine Letters*, 25: 196–203.

Petrova, V. I., 2001: Geochemistry of organic matter of estuary-shelf sediments of the Arctic area: PAH along the sea-river section. *In* Lisitsin, A. P., Vinogradov, M. E., and Romankevich, E. A. (eds.), *Experience of System Oceanologic Studies in the Arctic*. Moscow: Scientific World Press, 235–243 (in Russian).

Rachold, V., Grigoriev, M. N., Are, F. E., Solomon, S., Reimnitz, E., Kassens, H., and Antonow, M., 2000: Coastal erosion vs. riverine sediment discharge in the Arctic Shelf seas. *International Journal of Earth Sciences*, 89: 450–460.

Rachold, V., Steenhuisen, F., Odegard, R. S., and Atkinson, D. A., 2005: Geographical Information System to visualize and analyze circum-arctic coastal dynamics [abstract]. *In* Terra Nostra Heft 2: 2nd European Conference on Permafrost. June 12–16, 2005, Potsdam, Germany, 165 pp.

Romanenko, F. A., 1998: Nekotorye osobennosti stroeniya I dinamiki rel'efa poberehzii severnogo Taimyra [Some peculiarities of relief structure and dynamics of Taymyr sea shore]. *In* Solomatin, V. I., Sovershaev, V. A., and Mazur, I. I. (eds.), *Dynamics of Russian Arctic Shores*. Moscow: Izdatelstvo MGU (MSU Press), 154–169 (in Russian).

Romankevich, E. A., and Vetrov, A. A., 2001: *Tsikl ugleroda v Arkticheskikh moryakh Rossii [Cycle of Carbon in the Russian Arctic Seas]*. Moscow: Nauka Press, 302 pp. (in Russian).

Shpolyanskaya, N. A., and Streletskaya, I. D., 2004: Geneticheskie tipy plastovykh ldov i osobennosti ikh rasprostraneniya v Rossiiskoi Subarktike [Genetic types of massive ground ices and peculiarities of their distribution in Russian Subarctic]. *Kriosfera Zemli [Earth Cryosphere]*, VIII(4): 56–71 (in Russian).

Shpolyanskaya, N. A., Badu, Yu. B., and Streletskaya, I. D., 2002: Pazvitie morskikh beregov zapadnogo sektora rossiiskoi Arktiki v Pleistoksene [Development of sea coast line of western Russian Arctic in the Pleistocene period]. *Kriosfera Zemli [Earth Cryosphere]*, 6(4): 13–24 (in Russian).

Shur, Yu. L., Vasiliev, A. A., Veisman, L. I., Maksimov, V. V., Zaikanov, V. G., and Petrukhin, N. P., 1984: Metody izucheniya skorosti termoabrazii [Methods of Termoabrasion Rate Investigation]. *In* Are, F. E. (ed.), *Beregovye protsessy v kriolitozone [Coastal Processes in Permafrost]*. Novosibirsk: Nauka Press, 5–12 (in Russian).

Solomatin, V. I. (ed.), 1992: *Geoekologiya Severa (vvedenie v geokrioekologiyu) [Geoecology of the North (Introduction in Cryogeoecology of the North)]*. Moscow: Izdatelstvo MGU (MSU Press), 270 pp. (in Russian).

Stein, R., and Macdonald, R. W., 2003: Organic carbon budget: Arctic Ocean vs. Global Ocean. *In* Stein, R., and Macdonald, R. W. (eds.), *The Organic Carbon Cycle in the Arctic Ocean*. Berlin: Springer-Verlag, 169–177.

Stein, R., Niessen, F., Dittmers, K., Levitan, M., Schoster, F., Simstich, J., Steinke, T., and Stepanets, O., 2002: Siberian river run-off and Late Pleistocene glaciation in the southern Kara Sea, Atlantic Ocean: preliminary results. *Polar Research*, 21(2): 315–322.

Streletskaya, I. D., Ukraintseva, N. G., and Drozdov, I. D., 2003: A digital database on tabular ground ice in the Arctic. *In* Philips, M., Springman, S. M., and Arenson, L. U. (eds.), Proceedings of the 8th International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland. Rotterdam: A. A. Balkema Publishers, 2: 1107–1110.

Streletskaya, I. D., Kanevskiy, M. Z., and Vasiliev, A. A., 2006a: Plastovye l'dy v dislotsirovannykh chetvertichnykh otlozheniyakh zapadnogo Yamala [Massive ground ice in dislocated Pleistocene sediments of western Yamal]. *Kriosfera Zemli [Earth Cryosphere]*, X(2): 68–78 (in Russian).

Streletskaya, I. D., Vasiliev, A. A., Vanshtein, B. G., and Shirokov, R. S., 2006b: Organicheskii uglerod v chetvertichnykh otlozheniyakh Karskogo moray [Organic carbon in the coastal Pleistocene sediments of the Kara Sea]. *Kriosfera Zemli [Earth Cryosphere]*, X(4): 35–43 (in Russian).

Streletskaya, I. D., Vasiliev, A. A., and Vanstein, B. G., 2008: Organic carbon spatial distribution in Quaternary sediments of Russian West Arctic (fresh data). *In* Overdune, P., and Couture, N. (eds.), Reports on Polar and Marine Research. The 6th Annual Arctic Coastal Dynamic (ACD) Workshop, Oct. 22–26, 2006, Groningen, Netherlands. *Berichte*, 576: 83–84.

Svendsen, J. I., Astakhov, V. I., Bolshiyanov, D. Yu., Demidov, I., Dowdeswell, J. A., Gataulin, V., Hjort, C. h., Hubberten, H. W., Larsen, E., Mangerud, J., Melles, M., Moller, P., Saarnisto, M., and Siegert, M. J., 1999: Maximum extent of the Eurasian ice sheets in the Barents and Kara Sea region during the Weichselian. *Boreas*, 28: 234–242.

Trofimov, V. T., Badu, Yu. B., Kudryashov, V. G., and Firsov, N. G., 1975: *Poluostrov Yamal (Inzhenerno-geologicheskii ocherk) [Yamal Peninsula (engineering-geological essay)]*. Moscow: Izdatelstvo MGU (MSU Press), 276 pp. (in Russian).

Troitskii, S. L., and Kulakov, A. P., 1976: Kolebaniya urovnya okeana I rel'ef poberezhii [Sea-level changes of ocean and coastal relief]. *In* Yanshin, A. L. (ed.), *Problemy eksogennogo rel'efoobrazovaniya [Problems of exogenesis relief formation]*. Book 1. Moscow: Nauka Press, 351–426 (in Russian).

Vasiliev, A. A., 2003: Permafrost controls of coastal dynamics at the Marre-Sale key site, Western Yamal. *In* Philips, M., Springman, S. M., and Arenson, L. U. (eds.), Proceedings of the 8th International Conference on Permafrost, 21–25 July 2003, Zurich, Switzerland. Rotterdam, A. A. Balkema Publishers, 2: 1173–1178.

Vasiliev, A. A., 2004: Dynamics of Russian shores in cryolithozone of Western part of Russian Arctic (by the example of Kara Sea). Abstract of doctoral thesis. Tyumen: Faculty of Geology of MSU Press, 49 pp. (in Russian).

Vasiliev, A. A., 2005: Natural environment effect on sea coast dynamics of western part of Russian Arctic. *Kriosfera Zemli [Earth Cryosphere]*, IX(3): 64–72 (in Russian).

Vasiliev, A. A., Pokrovskii, A. A., and Shur, Yu. L., 2001: Dynamic of the coastal thermoerosion of West Yamal. *Kriosfera Zemli [Earth Cryosphere]*, 5(1): 44–52 (in Russian).

Vasiliev, A. A., Streletskaya, I. D., Cherkashov, G. A., and Vanshtein, B. G., 2006: Coastal dynamics of the Kara Sea. *Kriosfera Zemli [Earth Cryosphere]*, X(2): 56–67 (in Russian).

Voskresenskii, K. S., and Sovershaev, V. A., 1998: Rol ekzogennykh protsessov v dinamike Arkticheskikh poberezhii [Role of exogenous processes in a shore's dynamics of Arctic Seas]. *In* Solomatin, V. I., Sovershaev, V. A., and Mazur, I. I. (eds.), *Dynamics of Russian Arctic Shores*. Moscow: Izdatelstvo MGU (MSU Press), 35–48 (in Russian).

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