Biogeosciences Discuss., 8, 1917–1946, 2011
www.biogeosciences-discuss.net/8/1917/2011/
doi:10.5194/bgd-8-1917-2011

Biogeosciences Discussions

Seasonal and interannual variability of sedimentation and organic matter distribution in the Buor Khaya Gulf – the primary recipient of input from Lena River and coastal erosion in the SE Laptev Sea

A. N. Charkin[1], O. V. Dudarev[1], I. P. Semiletov[1,2], A. V. Kruhmalev[1], J. E. Vonk[3], L. Sánchez-García[3], E. Karlsson[3], and Ö. Gustafsson[3]

[1]Pacific Oceanological Institute (POI), Russian Academy of Sciences, Vladivostok, Russia
[2]International Arctic Research Center, University of Alaska Fairbanks, USA
[3]Department of Applied Environmental Science (ITM) and the Bert Bolin Centre for Climate Research, Stockholm University, Sweden

Received: 8 February 2011 – Accepted: 8 February 2011 – Published: 28 February 2011

Correspondence to: A. N. Charkin (charkin@poi.dvo.ru)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Climate warming is amplified in the land-sea system of the East Siberian Arctic, which also holds large pools of vulnerable carbon in permafrost. This coastal area is strongly influenced by sediment and carbon transport from both its large rivers and extensive erosion of Pleistocene permafrost along its coastline. This study is investigating the coastal fate of the sediment and organic carbon delivered to the Buor-Khaya Gulf, which is the first recipient of the 16 overwhelming fluvial discharge from the Lena River and is additionally receiving large input from extensive erosion of the coastal ice-complex (permafrost a.k.a. Yedoma; loess soil with high organic carbon content). Both water column suspended particulate matter (SPM) and surface sediments were sampled at about 250 oceanographic stations in the Gulf in this multiyear effort, including one winter campaign, and analyzed for the distribution and sorting of sediment size, organic carbon content, and stable carbon isotope signals. The composition of the surface sediment suggests an overwhelmingly terrestrial contribution from both river and coastal erosion.

Based on data collected during several years in the period 2000–2008, two different sedimentation regimes were revealed for the Buor-Khaya Gulf, the relative importance of each at a given time depend on hydrometeorological conditions, the Lena River water discharge and sea-ice regime: Type 1 *erosion-accumulation* and Type 2 *accumulation*.

The Type 1 *erosion-accumulation* sedimentation regime is typical (2000–2006) for the ice-free period of the year (here considered in detail for August 2005). Under such conditions terrigenous sources of suspended particulate matter (SPM) and particulate organic carbon (POC) stem predominantly from river discharge, thermal erosion of coastal ice-complex and remobilized bottom sediments. The Type 2 *accumulation* sedimentation regime develops under ice-covered conditions, and only occasionally during the ice-free period (August 2008). In Type 2 winter, combined terrigenous and marine-biogenic SPM and POC sources are dominating due to relatively low overall

terrigenous input (April 2007). In Type 2 summer, river alluvium becomes the major SPM and POC source (August 2008). The water column SPM and POC loadings vary by more than a factor of two between the two regimes. This study underscores the necessity of multi-year investigations to better understand the functioning of the primary recipient of terrestrially expulsed matter in the East Siberian Arctic.

1 Introduction

The Arctic Ocean receives >10% of the global river sediment discharge while only hosting 1% of the total ocean volume. The northeast Siberian land-shelf region is one of the areas on earth experiencing the strongest climate warming (e.g., Richter-Menge and Overland, 2010). Furthermore, the East Siberian Arctic Shelf (ESAS) is the world's largest continental shelf sea system and it is unusually shallow making the coastal system strongly influenced by terrestrial input. Nevertheless, there is a shortage of interannual and seasonal investigations of the coastal processing of the delivered sediment and its associated carbon content in this region (most previous studies have provided a snapshot from a single expedition).

The Buor-Khaya Gulf in the SE Laptev Sea was targeted for this study as it is both the primary recipient of the Lena River discharge and a hotspot for erosional input from the thermo-abraded coastal ice-complex of Pleistocene permafrost. About 80–90% of the Lena River water and up to 85% of its sediment discharge enters the Buor-Khaya Gulf (Fig. 1) divided between the three eastern delta channels: the Sardakhsko-Trofimovskaya system (60–75% of water discharge and up to 70% of sediment discharge), Bykovskaya (20–25% of water discharge and 15% of sediment discharge), Olenekskaya and Tumatskaya (5–10% of water discharge and 10% of sediment discharge) (Antonov, 1987; Sidorov, 1992). There are discussions concerning how much of the sediment transported by the Lena River actually reaches the Laptev Sea (Are et al., 2000). For example, one publication states that only 10–17% of the sediment

BGD
8, 1917–1946, 2011

in the lower Lena River at Kyusur makes it through the Lena Delta (Alabyan et al., 1995), whereas another paper argues that essentially all suspended sediments reach the Laptev Sea (Rachold et al., 2000).

Up to 30% of the coastline of the Buor-Khaya Gulf is composed of the steep (up to 30 m) relief of the ice-complex (yedoma), which is rapidly collapsing under thermal abrasion and accelerated wind/wave erosion due to the longer ice-free season and larger wave fetch. For instance, the coastline of Muostakh Island, located in the Buor-Khaya Bay, is retreating on average 11 m yr^{-1} (Grigoryev et al., 2000). The ice-complex is also widely spread within the Lena River Delta where its average annual retreat rate is 2–3 m yr^{-1} (Grigoryev, 1993). Hence, the Gulf's sedimentary material is stemming from two major sources: fluvial sediment discharge from the Lena River and thermal collapse and erosional input from the coastline ice-complex. Since hydrometeorological conditions and the Lena water discharge varies interannually (Savelieva et al., 2001; Pipko et al., 2010; Semiletov et al., 2011), it should be expected that the relative importance of these two sediment sources are also varying interannually, which in turn should be reflected in the composition of the water column suspended particulate matter (SPM) and of the bottom sediments (Charkin et al., 2010).

The objective of this paper is to shed light on the seasonal (i.e., winter vs. summer) and interannual variability of these coastal sedimentation processes and the dynamics of organic carbon (OC) distribution in both the water column SPM and the surface sediments of the Buor-Khaya Gulf.

2 Material and methods

2.1 Expeditions

Observations and sampling were performed in the Buor-Khaya Gulf (southeast Laptev Sea) on several separate expeditions using the mid-size hydrographic vessel Nikolai Kolomeitsev (2000), and the small vessels Auga (2005) and TB-0012 (2006–2008). In March–April 2007 an exploratory survey was performed on the land-fast sea ice to collect data for winter conditions using a transport caravan consisting of a caterpillar, a heavy all-terrain truck and a sled train, hosting laboratory and accommodations. During the whole survey period 250 complex oceanographic stations were accomplished with the bulk of the marine data for this paper being collected in August 2005, March–April 2007 and August 2008 expeditions. Furthermore, observations and sampling were also performed at key sections of the coastline, including Muostakh Island, Buor-Khaya Cape and Lena delta channels with samples taken from the tidal flat, the beach and up along the steep coastal abrasion cliff (Fig. 1).

2.2 Analytical methods

Size composition of fine grained sediments and SPM was studied using a laser micro-analyzer (Analysette, Fritsch GmbH). Sieve analysis was used for coarse sediments examination (Petelin, 1961). Bottom sediment sizing was then performed on the basis of a three-component classification (Shepard, 1954) with the definitions of sand (1–0.1 mm), silt (0.1–0.01 mm) and clay (<0.01 mm) fractions.

The SPM content was obtained by filtration through membrane filters with pore diameter of 0.47 µm followed by gravimetry. The particulate OC (POC) composition was analyzed on samples filtered onto borosilicate glass fiber filters (GF/F; Whatman Inc. with approximate pore diameters of 0.7 µm). Elementary (OC) and isotopic (δ^{13}C) composition of bottom sediment were determined by Carlo Erba elemental analyzers and a Finnigan MAT Delta Plus mass spectrometer, respectively, at the International Arctic Research Center, University of Alaska, Fairbanks (USA) and with similar instruments at Stockholm University (Sweden). Accuracy and reproducibility of the isotope results were within δ^{13}C ±0.1‰.

Study of the thermohaline structure of the water column was performed using a Conductivity-Temperature-Depth (CTD) sensor package (SeaBird 19Plus). The character of the vertical structure was evaluated by the Hanssen-Rattray (δS) parameter determined as a function of the salinity deviation at the bottom and at the surface to the average vertical deviation (Hanssen et al., 1966).

BGD
8, 1917–1946, 2011

3 Results and discussion

3.1 Sediment material transport and distribution

3.1.1 August 2005 survey

The Lena River 2005 discharge was one of the lowest (annual discharge was 617 km^3) for the period 1999–2008 and the August survey period coincided with the minimal river water level. South and south-easterly winds with average velocity of 11–12 $m\,s^{-1}$ prevailed in the Buor-Khaya Gulf. During such windy conditions, the water column in the area adjacent to the Lena Delta was mixed down to the bottom (depth of ∼8 m) (Fig. 2). However, for most of the Buor-Khaya Gulf, the water column remained moderately stratified (Fig. 2). Salinity varied from 4.9–12.1 in the surface layer and up to 8.9–31.5 in the bottom layer (Table 1). The surface water temperature varied from 3.5 °C in the northeast of the Gulf up to 5.5 °C along the marine margin of the delta with corresponding bottom water temperatures of 5 °C and 0.9 °C, respectively (Table 1).

Storm surge onto the continental coast creates favorable conditions for intense coastal erosion. As a result of bottom sediment resuspension, SPM in the near-bottom water layer reached 187 $mg\,l^{-1}$ (average 57.9 $mg\,l^{-1}$), which is possible when the critical shear stress (P) of the bottom sediments is exceeded (Beach et al., 1992). According to this criteria, when the Beach-Sternberg P value is $0.8 < P < 2.5$ and the dynamic flow velocity u^* is about 25 $cm\,s^{-1}$, sedimentary material can be resuspended and transported in the Buor-Khaya Gulf as SPM.

The value is calculated as a function of wet density (ws) divided by the product of u^* and the unitless Karman constant $k = 0.4$ (Beach et al., 1992).

$$P = \mathrm{ws}/ku^* \quad (1)$$

The following initial parameters were used: average particle wet density of 1.55–1.75 $g\,cm^{-3}$, actual current rates during the ice-free period of 10, 25, 50 and 100 $cm\,s^{-1}$ (Voinov, 1994; Navigational book, 1998). Under normal hydrometeorological conditions

BGD
8, 1917–1946, 2011

(u^* ~10 cm s^{-1}) the main type of particle transportation thus occurs in SPM (<0.6). The SPM values did not exceed 45 mg L^{-1} (average 17.5) in the surface water layer (Fig. 3, Table 1). SPM concentrations in the Lena tidal flat area located close to the intensively degrading northern coast of Muostakh Island were up to 594 mg L^{-1}.

POC content in the surface water varied from 0.13 mg L^{-1} (NE Buor-Khaya Gulf) up to 1.7–2.0 mg L^{-1} (Muostakh Island region) (Fig. 4). Maximum POC content in bottom waters exceeded 2.0 mg L^{-1} and was observed in the nepheloid layer, shallow waters around Muostakh Island, sediments underlying deeper waters and near the prodelta. The OC content in bottom sediments varied from 1% along the estuary sea line and Buor-Khaya Gulf up to 4% along the prodelta, and in sediments underlying deeper waters (Fig. 4). Spatial variability of the OC content in bottom sediments follows the sediment size distribution (Fig. 5).

The δ^{13}C-POC values in the surface water varied from −28.5‰ to −26.4‰ (Fig. 6). In bottom sediments the values varied from −22.9‰ near Muostakh Island to −26.3‰ within the prodelta. As a whole, sediment fields with δ^{13}C lighter than −25‰ prevailed (Fig. 6).

3.1.2 April 2007 survey

When the Buor-Khaya Gulf is ice covered, the Lena River influence (despite low discharge in winter) is reflected in water column stratification in the western part of the Gulf (Fig. 2). In the prodelta, salinity varied from 0.16–7.2 in the under-ice surface water to 0.7–23 in the bottom waters, while at greater distances from the delta the salinities increased to 13.9–15.4 in the surface layer and 25.2–27.4 in the bottom waters. Water temperatures were near-freezing everywhere except near outlets of the Lena channels where the Lena River heating effect is significant even in winter (Table 1).

The SPM content in April 2007 was low due to halted coastal erosion processes and low river flow. Maximum values of 11.8 mg L^{-1} at the surface and 15.2 mg L^{-1} at the bottom were detected at the Bykovskaya channel mouth. The average SPM values

BGD
8, 1917–1946, 2011

were 2.9 mg L^{-1} for under-ice surface waters and 4.8 mg L^{-1} in the bottom layer (Fig. 3, Table 1).

The POC content was also low and did not exceed 0.1 mg L^{-1}. Maximum values were detected in front of the channel outlets and north of the prodelta. Fluvial sources of POC is indicated by δ^{13}C values hovering about −29‰. A POC plume with δ^{13}C values of −23.6‰ was detected opposite of the Bykovskaya channel mouth.

The OC concentration in the prodelta surface sediments varied from 2.5–9.2%, which is higher than summer conditions (Fig. 4). The δ^{13}C-OC in surface sediments generally varies within the range from −25 to −27‰ except for the eastern continental-oriented slope of the Muostakh Island where the isotopic signature is unusually heavy for this area: −22.6‰ (Fig. 6).

3.1.3 August 2008 survey

The discharge of the Lena River was abnormally high in 2008 (annual discharge 716 km^3). This influenced the salinity, temperature and water column stratification throughout the Buor-Khaya Gulf. Similar to 2005 our survey was performed during the low-water period. Gentle south and southeast winds (1–2 m s^{-1}) prevailed in the Buor-Khaya Gulf during this survey period. The low winds and large freshwater discharge created a strongly stratified water column throughout the Buor-Khaya Gulf all the way to the 4 m isobath outside the Lena river delta (Fig. 2). Salinity varied from 0.1 at the surface to 24.5 at the bottom, and temperature varied from 16.2 °C to 2.6 °C, respectively. Moving east to the deeper parts of the Buor-Khaya Gulf the salinity was 2.6 and temperature 14.1 °C in the surface layer while the near-bottom waters had a salinity of 28.9 and temperature below zero (−1.3 °C). The prevailing hydrometeorological conditions thus caused a well-defined Lena River freshwater lense throughout the Gulf. The poor vertical mixing caused most of Buor-Khaya Gulf to keep remnant winter bottom water characteristics with low temperature (0.4 °C to 1.37 °C) and high salinity (24.7 to 28.9), respectively (Table 1).

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

The 2008 SPM values in the Buor-Khaya Gulf surface waters spanned 2.1–64.2 mg L^{-1} (average 11.2 mg L^{-1}), and in the bottom waters 3.2–64.6 mg L^{-1} (average 13.4 mg L^{-1}). The maximum values were detected in the river plume outside the mouth of Sardakhsko-Trofimovskaya channels. The August-2008 SPM loadings were low relative to August-2005, which is more representative of general conditions in the multi-year observations. The 2008 SPM values were 1.5 times lower in the surface layer and four times lower in the bottom water layer (Table 1).

The POC content in the surface water layer of the Buor-Khaya Gulf varied from 0.24–1.1 mg L^{-1} with the maximum values detected in the river plume outside to the mouth of Sardakhsko-Trofimovskaya channels. The POC-δ^{13}C in the surface water layer varied from –26.4‰ near the river mouth to –29 to –32‰ in the offshore part of the Buor-Khaya Gulf (Fig. 6). These highly depleted POC-δ^{13}C has been suggested to reflect a contribution from primary production based on pre-depleted terrestrial DIC-δ^{13}C (Sánchez-García et al., 2011).

Maximum OC content in surface sediments was also found near the mouth of the Sardakhsko-Trofimovskaya channels. OC values decreased eastward from 6% to 1–2% in the central part of the Buor-Khaya Gulf (Fig. 4). As in previous years, lowest OC values were detected in the NE corner of the Buor-Khaya Gulf study polygon (Fig. 4). The δ^{13}C-OC of the surface sediments was similar in 2008 to that of 2005. This may either reflect that the relative source contributions were similar and just experiencing different extents of dilution or that the δ^{13}C signals are not well separated between the river and erosion end members. This latter has recently been suggested (e.g., Vonk et al., 2010a) and the distinction between the two may be more approachable with δ^{14}C measurements (e.g., Vonk et al., 2010b; Karlsson et al., 2011).

3.2 Two different regimes for particle delivery and sedimentation

Two types of sedimentation regimes were defined on the basis of the obtained results: Type I *erosion-accumulation* (summers of 2000, 2005–2007) and Type II *accumulation* (winter periods, summer of 2008). These two regimes are schematically and

BGD
8, 1917–1946, 2011

photographically visualized in Fig. 7. The sedimentation dynamics are determined by complex interaction between the hydrometeorological conditions, river discharge, and sea-ice regime in the Lena River Delta and in the recipient Buor-Khaya Gulf. Below we describe these two dominant sedimentation regimes based on the most detailed years of observations taken in summers (August 2005 and 2008) and winter (April 2007).

3.2.1 Sedimentation regime: erosion-accumulation (Type I)

The erosion-accumulation sedimentation regime is characterized by hydrometeorological processes such as storm surges and strong currents. This regime was studied in detail in August 2005 and also observed in the summer periods of years 1999, 2000, 2006 and 2007 (data not shown). Most of these summer period surveys in the Buor-Khaya Gulf were executed during or right after severe storms. Such conditions are of high repeatability (63%) and long duration (up to 10 days) and therefore are typical for these waters during the ice-free period (Navigation book, 1998).

The prevailing strong winds in the Gulf results in considerable storm surges and pressures on the Gulf coastline (Navigation book, 1998). Hence, this creates favorable conditions for erosion of both the coastal ice-complex and of the bottom sediments, resulting in elevated SPM levels (Fig. 3). As noted above, conditions for bottom sediment erosion/resuspension are possible when the near-bottom shear stress exceeds the critical sheer stress value (Beach et al., 1992). If the dynamic flow velocity is 25 cm s^{-1} or higher, less cohesive bottom sediments can simultaneously be transported both as water column SPM and in the bottom nepheloid layer. At first only fine particles such as low-density organic and organo-mineral aggregates/flocculates are remobilized. As the flow velocity grows, heavier mineral particles become part of the SPM (Beach et al., 1992; Longinov, 1973) (Fig. 7). Consistent with these hydrodynamic expectations maximum SPM content in summer of 2005 was found in the Lena River prodelta at depths less than 8 m. As under the storm conditions ascending and descending vectors of turbulent exchange are mutually balanced (Bowden, 1983; Longinov, 1973; Leontyev, 2001), the SPM content is vertically well-mixed throughout the water column. The bottom water nepheloid layer is distinctly marked by the stratification, salinity, temperature and SPM (Figs. 2, 3, 7). Further offshore, the intensity of these hydrodynamic processes is weakened, which is reflected in stratification of the water column and its SPM content. The SPM content decreased by 10–15 times over the abrasion-accumulation plain in the central part of the well-stratified Buor-Khaya Gulf compared with in the shallow waters (Figs. 1, 2 and 7). Salinity increased here twofold and near-bottom temperatures decreased down to negative values.

With a wave height (H) in the Buor-Khaya Gulf of 2.5–3.0 m and a depth of 25–30 m, the algorithm: $h\text{crit} = 10H$ (Longinov, 1973) suggests that the direct wave impact zone may potentially be distributed over the whole Gulf. However, durability of such strong waves is short and the wave height in the Buor-Khaya Gulf usually does not exceed 1 m. This results in bottom erosion having the greatest impact at depths less than 10 m (Navigational book, 1998). This prediction is consistent with observations of coarse fractions of bottom sediments at these shallow depths (Fig. 5).

In this Type I sedimentation regime (*erosion-accumulation*), thermal and wave/wind abrasion of the coastal ice-complex is activated, resulting in large volumes of terrigenous material being remobilized into coastal waters (Fig. 7). During the last 300 yr under the thermal abrasion influence in the East Siberian Arctic, several islands in the Laptev Sea have disappeared under the water surface (Zemlya Sannikova, Figurina, Vasilyevskiy Island, Semyonovskiy Island) (Dudarev et al., 2006a). In addition to these well-known and named islands, the northeastern part of the Buor-Khaya Gulf is characterized by subsea relicts of past islands (Fig. 1). These subsea features have lithogenic characteristics (i.e., sand) that are consistent with recent (bottom) erosion of these island relicts rather than by hydrodynamically transported/sorted sedimentation (compare NE study region in Figs. 1 and 5).

Muostakh Island, located in the western Buor-Khaya Gulf, is composed of the Pleistocene ice-complex and has been studied by many investigators since the 1950s (e.g., Are, 1985, Grigoryev and Kunitsky 2000). Over the course of the last 50 yr, Muostakh Island has retreated strongly with a total erosion up to 700 m at the Northern Cape and

BGD
8, 1917–1946, 2011

average erosion rates of 14 m yr^{-1}. At the same time, the island width has decreased by 250–300 m at an average rate of 5–6 m yr^{-1} (Grigoryev and Kunitsky, 2000). Assuming that the width of the southern edge of the Bykovskiy Peninsula (1.3 km) and the current northern edge of Muostakh Island were similar at the time of their separation about 1.5–3 kyr ago, the millennium-scale average rate of island width decrease after separation is much lower and estimated to be only 0.3–0.5 m yr^{-1}. Apparently, the rate of erosion of Muostakh Island is much higher in recent decades than the average over the past few thousand years (Charkin et al., 2009).

Under the *erosion-accumulation* sedimentation (Type I) in the Buor-Khaya Gulf, the distribution of SPM, salinity, temperature and thus water column stratification is consistent with the distribution of the properties in the underlying bottom sediments and subwater reliefs (Figs. 2, 3 and 5). Size composition of bottom sediments is represented by sequential facies substitution in the direction from the delta to the central part of the Gulf with sands in the delta, silty sediments in the prodelta and clays making up the alluvial fan of the Lena River. Fine sediments also accumulate in the central part of deep erosion channels that extend several kilometers beyond the marine margin of the delta. Sedimentation of sands and coarse silts particles are thus reflected in the formation of the lithological pattern of the delta and prodelta. The regime of the prodelta foot (beyond the 5–10 m isobath) is characterized by silty sediments. At depths >10 m, the alluvial fan is formed. The surface of the accumulation-abrasion plane of the Gulf's deep-water part consists of clayey silt and silty clay sediments (Fig. 5). The structure of the SPM distribution and the hydrological characteristics coincides with the distribution of the bottom sediment structure and bottom reliefs, supporting the fact that the sedimentation Type I (*erosion-accumulation)* is the predominant mode for the ice-free summer period in the Buor-Khaya Gulf.

BGD
8, 1917–1946, 2011

3.2.2 Sedimentation regime: accumulation (Type II)

This accumulation-only type of sedimentation regime stably develops under ice-covered conditions, and in conditions of limited turbulent vertical mixing and absence of storm surges (i.e., long periods of low winds/waves). We found this type II of sedimentation in April 2007 and in August 2008.

The Buor-Khaya Gulf freezes up in mid-October. Depending on the volume of annual continental runoff, the thickness of fast ice varies between 1.9–2.4 m with its maximum in April. When ice cover halts the wave and surge activities, particles can settle undisturbed. Thus, the SPM content in the prodelta water column in winter was reduced 5–10 times (down to 5–10 mg L^{-1}) in comparison with the summer period (Fig. 3). In winter, the hydraulic velocity and the overall river discharge are low. In comparison with the summer period the SPM content in the mouth of the Bykovskiy channel is reduced by 2–3 times (down to 11 mg L^{-1}), and in the mouth of the Sardakhskaya channel more than 6 times (down to 9 mg L^{-1}) (Fig. 3).

With low discharge and absence of vertical wind-induced mixing, interaction between river water and seawater cause a stable frontal zone (Fig. 2). Superimposed on this feature are two well-defined freshwater plumes outside the mouths of the Bykovskiy and the Sardakhsko-Trofimovskaya delta channels affecting the distribution of many parameters (Figs. 2, 3, 4, 5, 6). Taken together, winter conditions are characterized by absence of measurable erosion and resuspension and low sedimentation-accumulation of riverine sediments.

August 2008 experienced an anomalous hydrometeorological situation with almost no winds and the highest Lena River discharge of our 1999–2008 study period. This resulted in a unique hydrological situation with strong stratification, a pycnocline as shallow as 4 m, with steep vertical gradients of temperature and salinity of 4°C m^{-1} and 7 m^{-1}, respectively. The average salinity in the surface layer was 3.5 times lower than for same month in 2005, while the temperature was twice as high (4.4 °C in 2005 and 10 °C in 2008) (Table 1). The calm weather during the ice-free period leads to

BGD
8, 1917–1946, 2011

formation of Type II sedimentation processes, which otherwise is normally observed only under winter conditions (Fig. 7).

The so-called backwater zone (i.e., countercurrents induced by high tides) plays an important lithodynamic role and represents a hydrodynamic sediment barrier for removal of part of the river SPM from transit to the ocean (Dudarev et al., 2006b). It is illustrated by the SPM distribution (Fig. 3). The SPM content in the surface layer at the marine margin of the prodelta decreased from 64 mg L^{-1} to 3 mg L^{-1}. At first, the coarse-grained particles defining SPM weight content are removed from the transport pathway. Abrupt settling of coarse material give rise to sand bars (Fig. 5). Further, with the river plume spreading further offshore, the flow velocity decreases to below the threshold where SPM remains in suspension and instead starts to settle. This is reflected in sediment sorting with a reduction of particle dimension in bottom sediments in an eastward direction (Fig. 5). The river alluvial fan of the Sardakhsko-Trofimovskaya channel outlets is well defined (Figs. 1, 2, 3, 5). This implies that the modern delta of the Lena River has been growing eastward in this area. This is also confirmed by the bottom relief and the structure of bottom sediments distribution (Figs. 1, 5).

There was much less input of OC from erosion of coastal ice-complex in summer of 2008 compared to normal summers. The ice-complex of Muostakh Island in 2008 did not experience considerable hydrodynamic impacts that is necessary for erosional input to the coastal sea. As a result, the velocity of shore regression was considerably slower and normal thermoabrasion processes were replaced by processes of thermodenudation and solifluction. In the absence of surges that normally wash thawing material out to sea, shore ledges were in 2008 instead blocked by debris from thawing of ice-complexes (Fig. 7). Thus, in summer of 2008 the SPM content in nearshore waters around Muostakh Island was reduced ∼150 times compared with summer of 2005, and did not exceed 4 mg L^{-1} (Figs. 3, 7). The isotopic composition of POC in the water column around the island was lighter (−29‰) than normal and pointed to a river source of SPM (Fig. 6). Thus, in 2008 the alluvial source dominated the SPM distribution in the Buor-Khaya Gulf (i.e., Type II sedimentation regime).

BGD
8, 1917–1946, 2011

3.3 Sources, transport and distribution of organic matter in the Buor-Khaya Gulf

The summertime POC concentrations in surface waters of the Buor-Khaya Gulf were similar during the different types of sedimentation (range of 0.13–2 mg L^{-1}) but the spatial distributions were different (Fig. 4). Under the Type I sedimentation regime (*erosion and accumulation*), highest POC levels were well-confined to a N-S band east of the delta, prodelta and around Muostakh island (Fig. 4). This is likely reflecting remobilization of OC from bottom sediments and input of OC from erosion-retreating coastal ice-complexes. Under Type II sedimentation regime (*accumulation*), highest POC levels were instead defined in an eastward extending river plume from the mouth of the Sardakhsko-Trofimovskaya delta channel system to the interior Buor-Khaya Gulf (Fig. 4). Thus the average POC content in surface waters in the central part of the Buor-Khaya Gulf in 2008 were twice as high as in 2005 (Fig. 4). Winter of 2007 had a similar spatial POC distribution as summer 2008 (Type II sedimentation regime), but with much lower concentrations.

The stable carbon isotopic composition ($\delta^{13}C$) of POC in the surface layer of August 2005 ranged from −26.4 to −28.5 (average −27.1‰) (Fig. 6). These values are typical for $\delta^{13}C$-POC from both the Lena River (Rachold et al., 1999; Semiletov et al., 2000; Dudarev et al., 2006b; Sanchéz-Garcìa et al., 2011) and from eroding ice-complex (Naidu et al., 2000; Semiletov et al., 2005; Dudarev et al., 2006c). The bottom sediments of the prodelta have a similar $\delta^{13}C$ signal (−26‰ to −27‰; Fig. 6), which is likely a mixture of terrigenous OC from coastal erosion and river discharge. Taken together, all of this is consistent with the sedimentary OC material in the Buor-Khaya Gulf with Type I sedimentation having several sources: river alluvium, ice-complex and SPM remobilized from the bottom.

The $\delta^{13}C$ of POC during Type II sedimentation varied greatly between summer 2008 conditions (as depleted as −32.2‰) and winter 2007 conditions as heavy as −23.6‰) (Fig. 6). The only similarity between summer and winter is that the eastward extending river plume is visible in the $\delta^{13}C$ signals. In the winter period, there is a sharp gradient

BGD
8, 1917–1946, 2011
Seasonal and interannual variability in the Buor Khaya Gulf
A. N. Charkin et al.

centered on the outer prodelta, with $\delta^{13}C$ values getting heavier eastward. This presumably reflects strong terrestrial influence from the river (delta side has value of −28 to −30‰) while at the marine side of the section, the values are −24.2 to −24.5‰, pointing to a mixture of terrigenous and marine sources (Fig. 6).

Despite abnormal summer conditions during 2008, starting $\delta^{13}C$-POC values in the delta/prodelta were similar, but became more and more depleted to fall below −30‰ over large areas in the central and NE Buor-Khaya Bay (Fig. 6). It has recently been argued that the fluvial organic matter is exported in two physical forms; as organic-rich low-density flocculates that stay suspended over long distances and as organic coatings on mineral particles, which are more rapidly settling (Vonk et al., 2010a, b). The $\delta^{13}C$ of surface sediments are consistent with a heavier $\delta^{13}C$ fraction settling out to balance the depleted $\delta^{13}C$ being transported further offshore with surface waters (Fig. 6). An additional, possibly complementary, explanation of the depleted $\delta^{13}C$-POC in surface waters of 2008 is that they reflect (also buoyant) phytoplankton and its debris. Photosynthesis that has occurred in the river is known to produce depleted $\delta^{13}C$ (Rachold et al., 1999; Semiletov et al., 2011). The depleted $\delta^{13}C$-POC is also consistent with coastal primary production using excess fluvial DIC carrying a depleted $\delta^{13}C$ relative to marine DIC and thus imprinting a negative bias of marine phytoplankton $\delta^{13}C$. This was hypothesized to explain similarly depleted $\delta^{13}C$-POC far offshore in the Laptev and East Siberian Sea, that also matched with depletion of other nutrients (Alling et al., 2010; Sánchez-García et al., 2011).

Erosion-accumulation type of sedimentation processes are characterized by drastic increase of the surface sediment OC concentration from 0.1% in coarse sands up to 5–6% in fine sediments of the prodelta foot and Muostakh Island slope. *Accumulative* type of sedimentation is characterized by settling of alluvial sediment material increasing the surface sediment OC from ~0.1% up to 8–9% in the prodelta (Fig. 4). Genesis of bottom sediments organic matter in the Buor-Khaya Gulf points at a mixed source with a prevalent contribution of products of ice-complex disintegration and river alluvium with $\delta^{13}C$ of −25‰ to −27‰.

BGD
8, 1917–1946, 2011

A δ^{13}C signal heavier than −24‰ was confined to grey sands of the underwater thermo-abrasive and accumulative terrace adjoining the Bykovskiy Peninsula, the southeast part of Muostakh Island and in sands on the beach of the central and southern part of eastern shore of Muostakh Island. The question of genesis of these sands remains open for discussion. We hypothesize, based on mineralogic and X-ray structural results (Fig. 8), that the organic fraction producing a heavy isotopic signal originates from metamorphized shales of Permian (299–255 Myr ago) deposits. Such Permian deposits were uncovered by boreholes, and in some places (the Bykovskiy channel) even exposed on the surface (Lazko, 1975).

Thus, we can state that the erosion-accumulation regime of sedimentation is characterised by dynamics of eroded POC and anomalously high OC content in the surface sediments in the prodelta foot and Muostakh Island slope, while the accumulative regime is characterized by alluvial POC transport and enhanced OC content near the river mouth.

4 Conclusions

This investigation has demonstrated the need to make interannual observations of high spatial resolution to deduce coastal sediment dynamics and OC transport and distribution processes on the East Siberian Arctic shelf. Based on long-term data (2000, 2005–2008) two types of sedimentation regimes have been revealed: (1) *erosion-accumulation*, and (2) *accumulation*. The *erosion-accumulation* conditions were observed during the short ice-free period of the year (expeditions in late August of 1999–2007). This is believed to be the most common and quantitatively most important mechanism for SPM and terrestrial POC delivery to these coastal systems. In this mechanism, terrigenous sources of SPM and POC prevail, originating from thermoabrasion of shores (coastal ice-complex), river sedimentary material and remobilized material from the bottom.

BGD
8, 1917–1946, 2011
Seasonal and interannual variability in the Buor Khaya Gulf
A. N. Charkin et al.

During the *erosion-accumulation* sedimentation regime, highest POC content was found outside the mouth of the delta channel, over the prodelta and around the rapidly eroding Muostakh Island. The highest OC content in surface sediments exists off the prodelta and in sediments around Muostakh Island with its eroding ice-complex. Under such conditions terrigenous sources of SPM and POC stem predominantly from river discharge, thermal erosion of coastal ice complex and remobilized bottom sediments.

The *accumulation* sedimentation regime develops under ice-covered (winter) conditions and in rare instances during the ice-free period (e.g., August 2008). Under these *accumulation* conditions, highest surface water POC contents are confined by the river plume opposite the mouth of the Sardakhsko-Trofimovskaya delta channel. *Accumulation* type of sedimentation is characterized by settling of fluvial sediment OC in Sardahski-Trofimovsky sector of the prodelta. In Type 2 winter, fluvial SPM and POC sources are dominating despitte relatively low overall terrigenous input (April 2007). In Type 2 summer, river alluvium is also the major SPM and POC source (August 2008). The water column SPM and POC loadings vary by more than a factor of two between the two regimes.

Acknowledgements. This work was supported by the Far-Eastern Branch of the Russian Academy of Sciences (FEBRAS), the International Arctic Research Center (IARC) of the University of Alaska Fairbanks, and by the Cooperative Institute for Arctic Research through NOAA Cooperative Agreement NA17RJ1224 and the National Science Foundation Agreement No. OPP-0327664, both with the University of Alaska. This research was also funded in part by the Russian Foundation for Basic Research (No. 04-05-64819, 10-05-00996- (IPS), the US National Science Foundation (grant OPP-0230455) and the Swedish Research Council (VR Contract No. 621-2004-4039 and 621-2007-4631). The 2008 expedition was carried out with logistic support from the Knut and Alice Wallenberg Foundation and the Swedish Polar Research Secretariat.

BGD
8, 1917–1946, 2011

References

Alabyan, A. M., Chalov, R. S., Korotaev, V. N., Sidorchuk, A., Yu, A. N. D., and Zaitsev, A. A.: Natural and technogenic water and sediment supply to the Laptev SEA, Rep. Polar Res., 182, 265–271, 1995.

Alling, V., Sanchez-García, L., Porcelli, D., Pugach, S. P., Vonk, J. E., Dongen, D., Mörth, C. M., Anderson, L. G., Sokolov, A., Andersson, P., Humborg, C., and Semiletov, I. P.: Nonconservative behavior of dissolved organic carbon across the Laptev and East Siberian seas, Global Biogeochem. Cy., 24, GB4033, doi:10.1029/2010GB003834, 2010.

Antonov, V. S.: Mouth area of the Lena river (hydrological sketch), Leningrad, Hydrometizdat, 107, p. 10, 1987.

Are, F. E.: Thermo abrasion of sea coasts, Novosibirsk, Science, p. 171, 1985.

Are, F. E. and Reimnitz, E.: An overview of the Lena river Delta setting: geology, tectonics, geomorphology, and hydrology, J. Coastal Res., 16, 4, 1083–1093, 2000.

Beach, R. A. and Sternberg, R.W.: Suspended Sediment transport in the surf zone: response to the incident wave and Longshore current interaction, Mar. Geol., 108, 275–294, 1992.

Bowden, K. F.: Physical oceanography of coastal waters, Ellis Horwood Ltd., Chichester, 302 pp., 1983.

Charkin, A. N., Dudarev, O. V., Semiletov, I. P., Vonk, J., Sanchez-Garcia, L., Gustafsson, Ö., Andersson, P., and Shakhova, N.: Sedimentation in the Lena river delta and adjacent part of the Laptev Sea, Geophys. Res. Abstr., 11, EGU2009-3341, EGU General Assembly, 2009.

Charkin, A. N., Dudarev, O. V., Semiletov, I. P., Gustafsson, Ö., Vonk, J., Sanchez-Garcia, L., and Krukhmalev, A.: Seasonal variability of particulate material concentration and its composition in the Buor Khaya Gulf, Laptev Sea, Geophys. Res. Abstr., 12, EGU2010-6179, EGU General Assembly, 2010.

Dudarev, O. V., Charkin, A. N. , Semiletov, I. P., Shilo, I. N., Salyuk, A. N., and Spivak, E. A.: The current state of submarian island relicts on the East Siberian Shelf, Dokl. Earth Sci., 419, 2, 255–261, 2006a.

Dudarev, O. V., Semiletov, I. P., and Charkin, A. N.: Particulate material composition in the Lena River-Laptev Sea system: scales of heterogeneities, Dokl. Earth Sci., 411A, 9, 1445–1451, 2006b.

Dudarev, O. V., Semiletov, I. P., Charkin, A. N., and Botsul, A. I.: Deposition settings on the continental Shelf of the East Siberian Sea, Dokl. Earth Sci., 409A, 6, 1000–1005, 2006c.

BGD

8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

Grigoryev, M. N.: Criomorphogenesis of the mouth area of the Lena river, Yakutsk: Institute of permafrost study of the Siberian Branch of the Russian Academy of Science, p. 176, 1993.
Grigoryev, M. N. and Kunitsky, V. V.: Ice complex of the Arctic coast of Yakutia as a source of detrital deposits on the shelf, Hydrometeorological and biogeochemical researches in Arctic regions, The Arctic Areal centre, Vladivostok: Dalnauka, 2, 1, 109–116, 2000.
Hansen, L. F., Stelts, M. L., and Wesolowski, J. J.: Ground-State (*p*, *n*) Reactions in Mirror Nuclei and the Quasielastic Model of (*p*, *n*) Reactions, Phys. Rev., 143, 800–807, 1966.
Karlsson, E. S., Charkin, A. N., Dudarev, O. V., Semiletov, I. P., Vonk, J. E., Sánchez-García, L., Andersson, A., and Gustafsson, Ö.: Carbon isotopes and lipid biomarker investigation of sources, transport and degradation of terrestrial organic matter in the Buor Khaya Bay – the primary recipient of input from Lena River and coastal erosion in the Laptev Sea, in this special issue.
Lazko, E. M.: Regional Geology of the USSR, 2 volumes, Vol. 2, The Asian part, M: Nedra, 12, 1975.
Leontyev, I. O.: Coastal dynamics: waves, currents, flows of detrital deposits, M, GEOS., 272 pp., 2001.
Longinov, V. V.: Sketches of Lithodynamics of the Ocean, M, Nauka, 243 pp., 1973.
Naidu, A. S., Cooper, L. W., Finney, B. P., Macdonald, R. W., Alexander, C., and Semiletov, I. P.: Organic carbon isotope ratios (δ^{13}C) of Arctic Amerasian continental shelf sediments, Int. J. Earth Sci. (Special issue: Arctic Paleo-River Discharge), 89, 522–532, 2000.
Navigational book of the Laptev Sea, GUNIO, St.-Petersburg, 278 pp., 1997.
Petelin, V. P.: New method of water-mechanical analyze of marine bottom sediment, Oceanology, 1, 143–148, 1961.
Pipko, I. I., Pugach, S. P., Dudarev, O. V., Charkin, A. N., and Semiletov, I. P.: Carbonate parameters of the Lena River: Characteristics and Distribution, Geochem. Int., 48, 11, 1131–1137, 2010.
Rachold, V. and Hubberten, H.-W.: Carbon isotope composition of particulate organic material in East Siberian rivers, in: Land-Ocean Systems in the Siberian Arctic: Dynamics and History, Springer-Verlag, Berlin, 224–237, 1999.
Rachold, V, Grigoriev, M. N., Are, F. E., Solomon, S., Reimnnitz, E., Kassens, H., and Antonow, M.: Coastal erosion vs. riverine sediment discharge in the Arctic shelf seas, Int. J. Earth Sci., 89, 450–460, 2000.
Richter-Menge, J. and Overland, J. E. (Eds): Arctic Report Card 2010, available at: http://www.

arctic.noaa.gov/reportcard/ArcticReportCard_full_report.pdf, 2010.
Sanchéz-García, L., Alling, V., Pugach, S., Vonk, J., van Dongen, B., Humborg, C., Dudarev, O., Semiletov, I., and Gustafsson, Ö.: Inventories and behavior of particulate organic carbon in the Laptev and East Siberian Seas, Global Biogeochem. Cy., in press, 2011.
Savelieva, N. I., Semiletov, I. P., Weller, G. E., and Vasilevskaya, L. N.: Empirical Evidence for North Asia Climate Shift in the Early 1970s, Hydrometeorological and biogeochemical researches in Arctic regions, The Arctic Areal centre, issue III, part. 1, Vladivostok: Dalnauka, 41–55, 2001.
Semiletov, I. P., Savelieva, N. I., Weller, G. E., Pipko, I. I., Pugach, S. P., Gukov, A. Y., and Vasilevskaya, L. N.: in: The Freshwater Budget of the Arctic Ocean, NATO Meeting/NATO ASI Series, Dordtrecht, Kluwer Acad. Publ., 323–366, 2000.
Semiletov, I. P., Dudarev, V. Luchin, A., Charkin, K., Shin, K.-H., and Tanaka, N.: The East Siberian Sea as a transition zone between Pacific-derived waters and Arctic shelf waters, Geophys. Res. Lett., 32, L10614, doi:10.1029/2005GL022490, 2005.
Semiletov, I. P., Pipko, I. I., Shakhova, N. E., Dudarev, O. V., Pugach, S. P., Charkin, A. N., McRoy, A. N., Kosmach, D., and Gustafsson, Ö.: On the Biogeochemical Signature of the Lena River from the Upper Stream to the Arctic Ocean, this issue, 2011.
Shepard, F. P.: Nomenclature based on sand-silt-clay ratios, J. Sediment. Petrol., 24, 151–158, 1954.
Sidorov, I. S.: Features of forming of hydrochemical regime of mouth area of the Lena river and southeast part of the Laptev Sea, synopsis of thesis Rostov-on-Don, 24, 1992.
Vonk, J. E., van Dongen, B. E., and Gustafsson, Ö.: Selective preservation of old organic carbon fluvially released from sub-arctic soils, Geophys. Res. Lett., 37, L11605, doi:10.1029/2010GL042909, 2010a.
Vonk, J. E., Sánchez-García, L., Semiletov, I., Dudarev, O., Eglinton, T., Andersson, A., and Gustafsson, Ö.: Molecular and radiocarbon constraints on sources and degradation of terrestrial organic carbon along the Kolyma paleoriver transect, East Siberian Sea, Biogeosciences, 7, 3153–3166, doi:10.5194/bg-7-3153-2010, 2010b.

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

Table 1. Temporal variability of core parameters for suspended particulate matter, bottom sediments and water column during three high-intensity campaigns.

Parameters		Type I: *Erosion-accumulation* August 2005 Surface water	Type I: *Erosion-accumulation* August 2005 Bottom water	Type II: *Acumulation* April 2007 Surface water	Type II: *Acumulation* April 2007 Bottom water	Type II: *Acumulation* August 2008 Surface water	Type II: *Acumulation* August 2008 Bottom water
Salinity	min.	4.9	8.9	0.24	0.7	0.1	9.3
	max.	12.1	31.5	15.4	27.4	8.4	28.9
	average	8.7	24.1	6.3	19.6	2.4	25.8
Temperature (°C)	min.	3.5	−0.9	−0.48	−0.7	5.2	−1.37
	max.	5.5	5.0	2.3	0.15	16.5	7.5
	average	4.4	1.1	0.06	−0.32	10.1	−0.43
SPM ($mg\,L^{-1}$)	min.	2.5	5.1	1.2	1.5	1.9	3.2
	max.	45	186.4	11	15.2	64	64.6
	average	17.5	57.9	2.9	4.8	11.2	13.4
Surface water POC ($mg\,L^{-1}$)	min.	0.13		0.03		0.24	
	max.	2.0		0.10		1.1	
	average	0.6		0.07		0.5	
Surface water δ^{13}C-POC (‰)	min.	−28.2		−29.9		−32.2	
	max.	−26.4		−23.6		−24.3	
	average	−27.1		−27.6		−28.6	
Surface sediments SOC (%)	min.	1.4		0.20		0.40	
	max.	4.2		9.0		6.0	
	average	2.9		3.7		2.05	
δ^{13}C Surface sediments δ^{13}C-SOC (‰)	min.	−26.5		−26.4		−26.6	
	max.	−22.9		−22.6		−25.3	
	average	−25.9		−25.6		−25.8	

BGD
8, 1917–1946, 2011

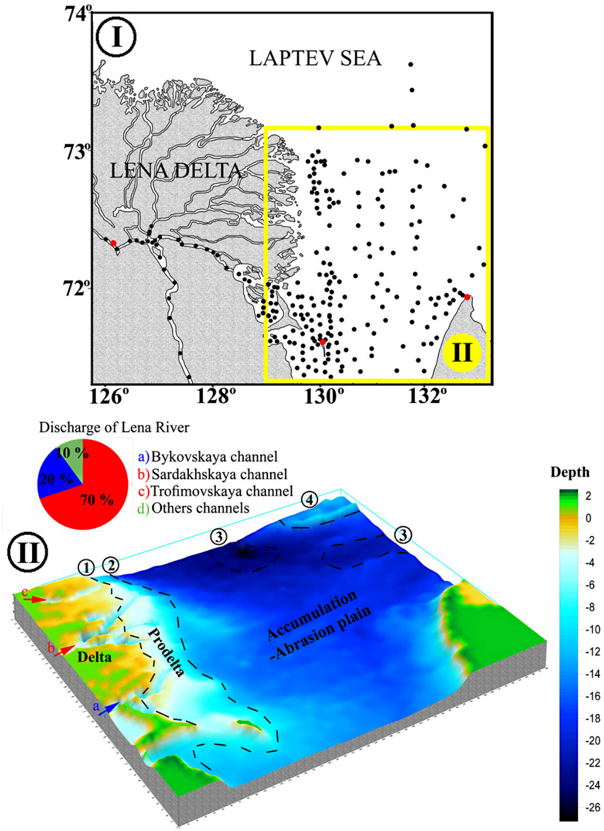

Fig. 1. Study Area. **(I)** Location of oceanographic stations from 1999 to 2008 yr (black dots: oceanographic stations, red dots: coast observations). **(II)** Flow chart of geomorphological structure of the Buor-Khaya Gulf: 1. marine margin of delta, 2. prodelta foot, 3. accumulative plain, 4. relict of subaerial land forms.

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

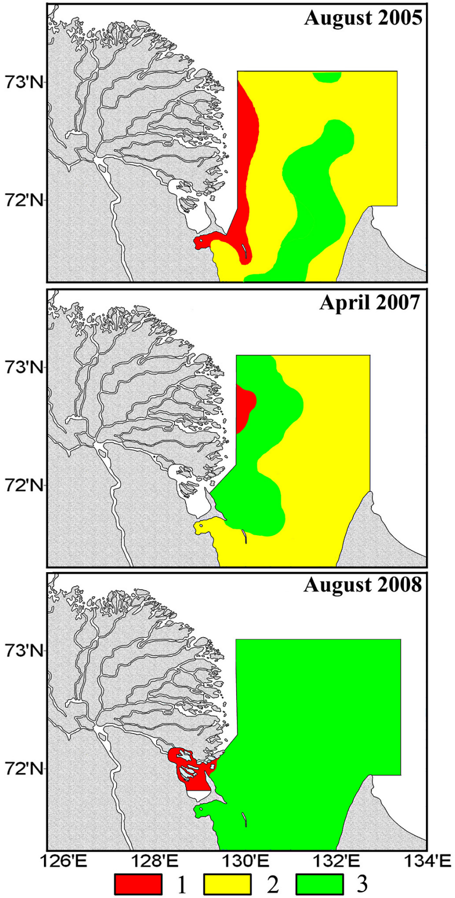

Fig. 2. Stratification of water column of the Buor-Khaya Gulf according to Hanssen-Rattri index: 1. intermixed waters, 2. medium-stratified, 3. stratified.

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

Title Page
Abstract Introduction
Conclusions References
Tables Figures
◀I ▶I
◀ ▶
Back Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

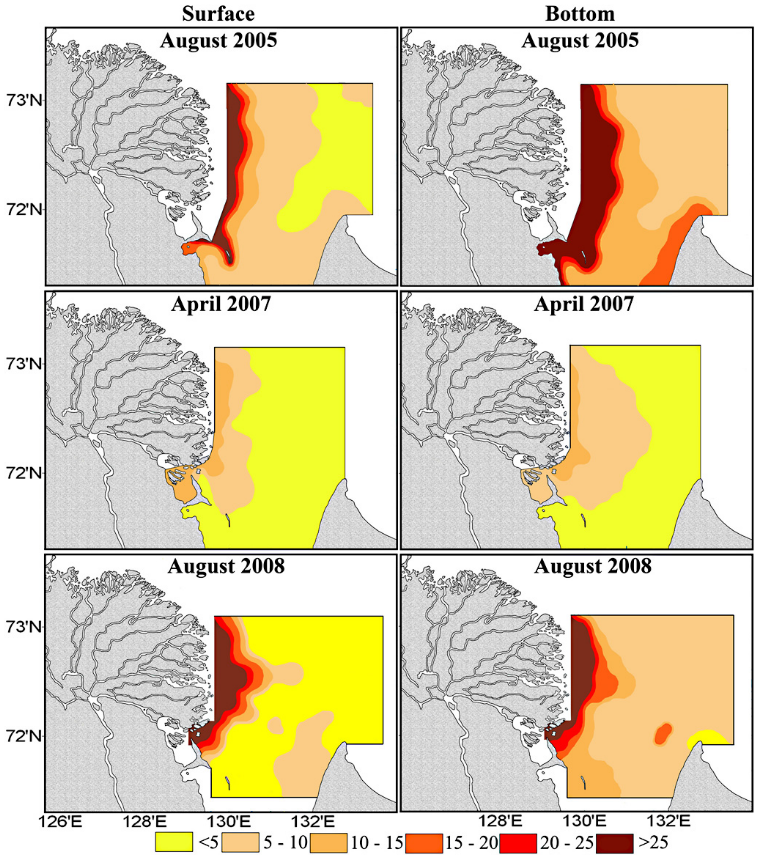

Fig. 3. Distribution of SPM ($mg\,L^{-1}$).

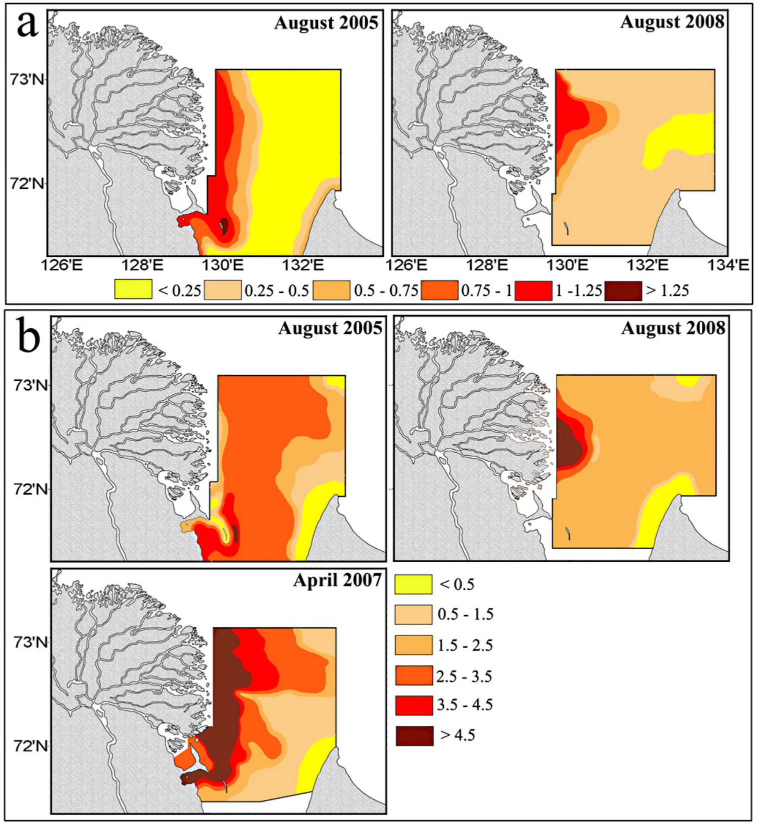

Fig. 4. OC content of **(a)** water column (POC; $mg\,L^{-1}$) and **(b)** bottom sediments (%).

BGD

8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

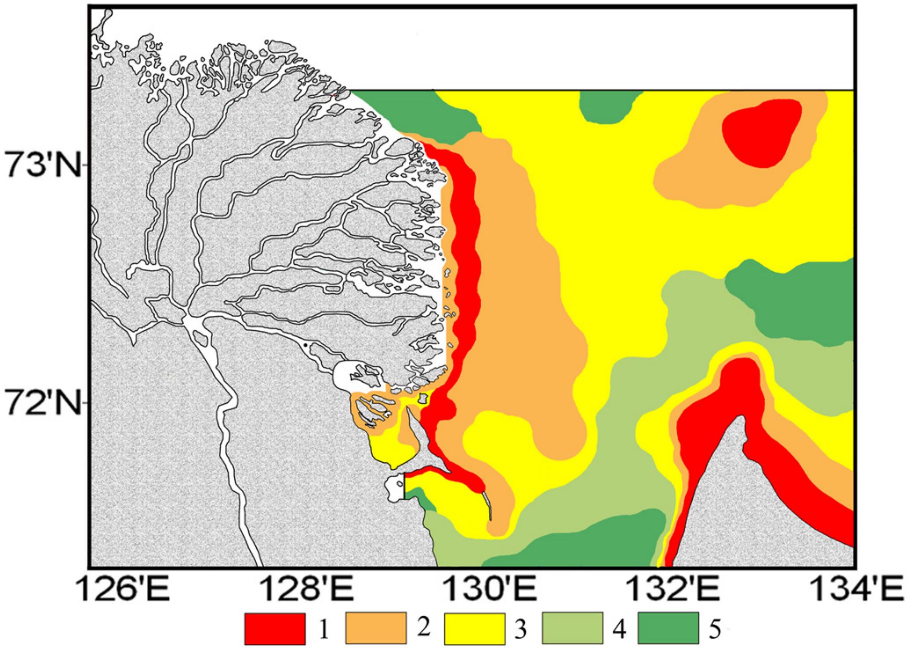

Fig. 5. Types of bottom sediments: 1. Sand, 2. Silty sand, 3. Clayey silt, 4. Silty clay, 5. Clay.

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.

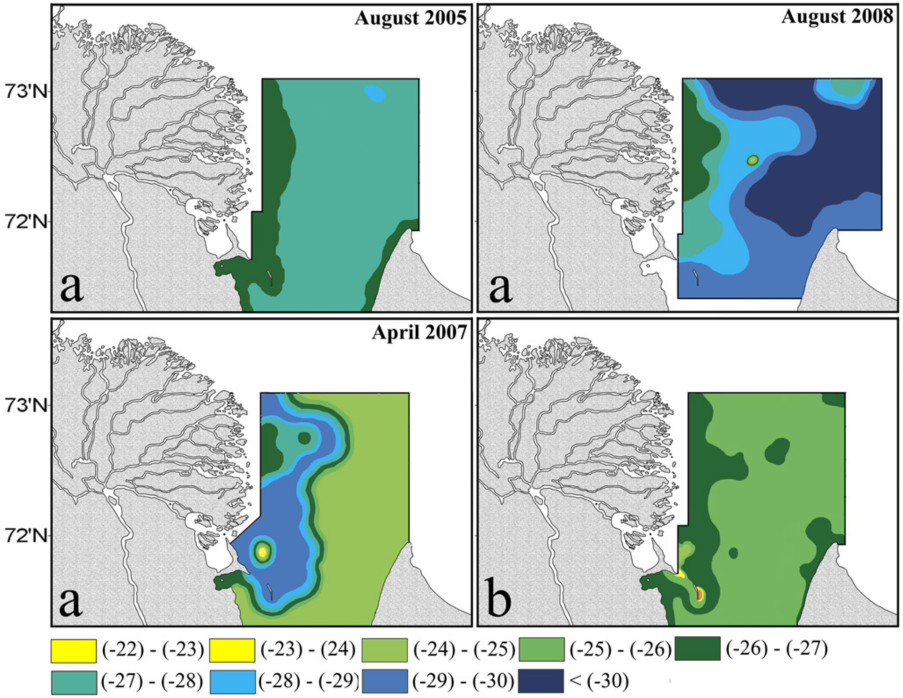

Fig. 6. $\delta^{13}C$ (‰) in **(a)** water column and **(b)** bottom sediments (combined 2000, 2005, 2007 and 2008 yr).

BGD
8, 1917–1946, 2011

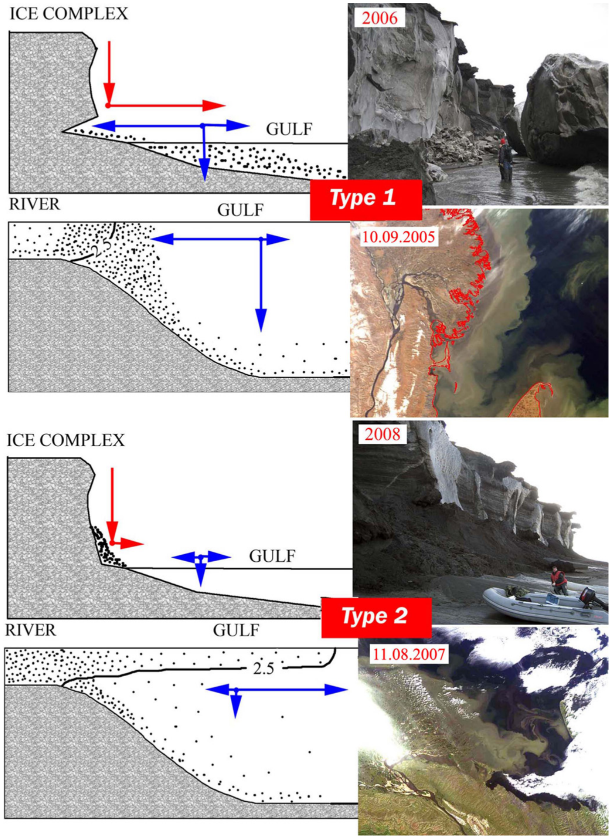

Fig. 7. Delivery scheme of sedimentary material from coastal ice-complex and mouths of the Lena River flow channels for two sedimentation regimes. Black points show concentration of sedimentary material, blue arrows show force and direction of movement of water, red arrows show intensity and direction of movement of flows of sedimentary material. Picture snapshots show northern coast of Muostakh Island at different sedimentation regimes. Satellite snapshots feature flows of SPM under various regimes of sedimentation.

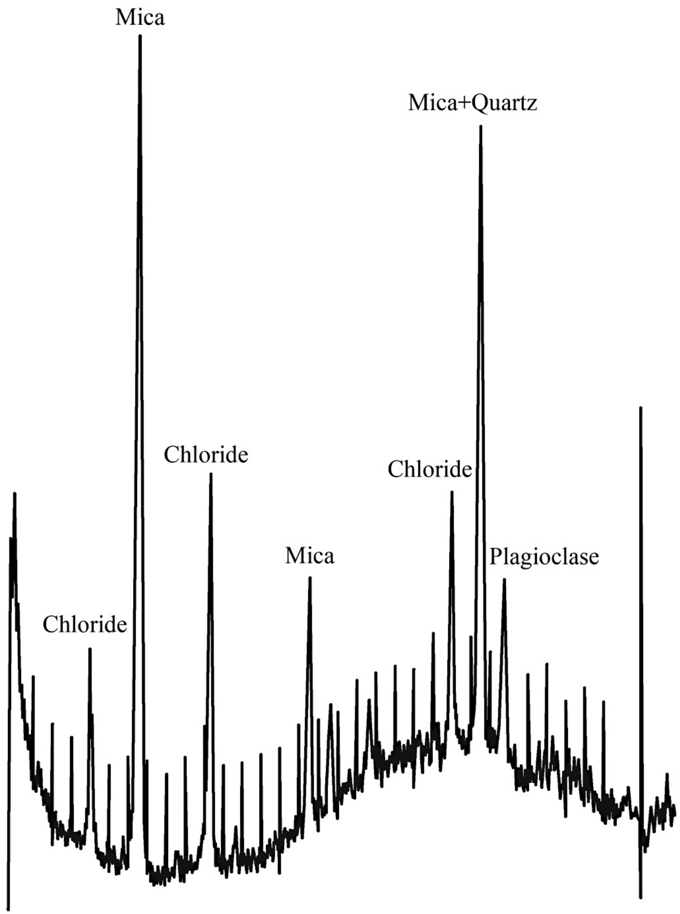

Fig. 8. X-ray structure of grey sands of Muostakh Island.

BGD
8, 1917–1946, 2011

Seasonal and interannual variability in the Buor Khaya Gulf

A. N. Charkin et al.