ISSN 0001-4370, Oceanology, 2015, Vol. 55, No. 4, pp. 623–643.

MARINE GEOLOGY

Genesis and Spatial Distribution of Suspended Particulate Matter Concentrations in the Kara Sea during Maximum Reduction of the Arctic Ice Sheet

M. D. Kravchishina, A. Yu. Lein, I. N. Sukhanova, V. A. Artem'ev, and A. N. Novigatsky

Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia

e-mail: kravchishina@ocean.ru, lein@ocean.ru, m_flint@orc.ru

Received September 23, 2014; in final form, October 29, 2014

Abstract—The suspended particulate matter (SPM) distribution in the water column of the Kara Sea including the Ob and Yenisei river estuaries was investigated in September 2007 and 2011, i.e., during periods of the maximum reduction of drift ice in the Arctic Ocean. The increased SPM concentrations in the surface layer of the Ob Estuary (26 and 16 mg/L on average in the fresh and saline (3–10 psu) water, respectively) were revealed in 2007 as compared with its values available from previous publications. The SPM concentrations and share of the terrigenous component in the latter in the Ob Estuary (2007) was ≥10 times higher than in the estuary of the Yenisei River (2011). The SPM concentration decreased exponentially in response to fresh and saline water mixing in the marginal filter (MF) areas of these rivers. The main transformation of the SPM composition at the transition from estuary to shelf waters took place within the salinity frontal zone (coagulation and sorption stage of the MF). The impact of terrigenous material on marine SPM composition in 2011 decreased in the northerly direction. The anomalous desalination of the sea surface layer in 2007 resulted in significant lightening of the organic carbon isotopic composition in the western part of the Kara Sea. This means that the impact of terrigenous material on SPM composition insignificantly decreased in the northerly direction. It was shown that mineral matter was distributed from the northeastern extremity of the Novaya Zemlya Archipelago in the northeasterly direction. At the same time, mineral particles transported by rivers from West and East Siberia prevail in the terrigenous SPM constituent in the Kara Sea up to 76°30′ N. Our data indicated that the processes of cross-shelf SPM transport in the Kara Sea were controlled by bottom topography.

DOI: 10.1134/S000143701503008X

INTRODUCTION

Suspended particulate matter (SPM) in sea basins is represented by biogenic material produced by planktonic organisms and abiogenic mineral material transported from land. The study of its composition is necessary for understanding recent sedimentation processes and transport routes of pollutant. The general features of SPM distribution in the Kara Sea discussed in [30, 34, 51, 54, 65] appeared to be characteristic also of other Arctic and subarctic seas [31, 33, 39].

Three large expeditions to the Laptev Sea, Lena River delta, Kara Sea, Ob and Yenisei river estuaries were carried out within the framework of the international SPASIBA project in 1989–1995 [10]. The first geological–geochemical researches of the SPM were carried out during the cruise of the R/V *Dmitry Mendeleev* to the Kara Sea in 1993.

The work during the cruise of the R/V *Professor Logachev* in 1964 included investigations in the St. Anna Trough [16]. The biogeochemical cycle of carbon (including its particulate form) in the Kara Sea and adjacent river network (Yenisei and Ob rivers) were studied within the framework of the Russian–German SIRRO project in 1997–2002 [8].

The first data on the isotopic composition of particulate organic carbon (POC) in the Kara Sea are available in [28]. Similar aspects are also discussed in [8, 17, 18, 56, 62, and etc.]. These researches demonstrated that the SPM composition is significantly influenced by the impact of terrigenous material, which decreases in the northerly direction.

The Russian–German cooperation in researches of the Arctic seas (Laptev, Kara) started in 1991, coinciding with the period of accelerated climatic changes in the Arctic region [44, 54]. The data on the SPM distribution in the Russian Arctic seas (which were carried out by involving hydrooptical methods among others) are reviewed in [33].

The investigations in the expeditions of the R/V *Ivan Petrov* in the Kara and Laptev seas in 2007–2008 organized by the Arctic and Antarctic Research Institute culminated in the compilation of maps illustrating the distribution of the SPM and hydrooptical parameters in these basins [5, 6].

In September–October 2007, the Shirshov Institute of Oceanology of the Russian Academy of Sciences (IO RAS) carried out complex investigations in Cruise 54 of the R/V *Akademik Mstislav Keldysh* (AMK) in the Kara Sea [49]. The anomalous temperature and salinity values of the surface water layer over most of the Arctic Ocean were considered extreme in summer 2007 [48]. September of 2007 was marked by a reduction of the Arctic ice sheet, the greatest one since the 1930s: residual ice cover (integral area of drift ice preserved after summer destruction and melting) was as large as 4.3×10^6 km^2 against the background of an ordinary area equal to 6.6×10^6 km^2 (1978–2009) [38, 45]. Such a decrease in ice area is explained by development of conditions favorable for supply of the Atlantic water mass to the Kara Sea during the spring–summer period [15, 38]. It is found that Atlantic waters serve as an additional source of sedimentary material into the St. Anna Trough [24].

The next important stage in the complex investigations in the Kara Sea was connected with Cruise 59 of the R/V *Akademik Mstislav Keldysh* in September 2011. As a whole, the summer maximum of ice cover development in 2011 was close to the absolute record registered in 2007 [38].

The purpose of this work is the study of main features in the SPM composition and its spatial distribution in the Kara Sea during the period of minimum ice cover development in the Arctic Ocean (2007 and 2011). Special attention is paid to the research of cross-shelf transport of terrigenous SPM supplied by the Ob and Yenisei rivers.

STUDY AREA

The Kara Sea is strongly influenced by river runoff and influx of terrigenous sedimentary material transported by the latter. The influx of the SPM supplied by the Ob and Yenisei rivers is as high as 15.5×10^6 and 4.7×10^6 t/year, respectively (in the area of the Igarka and Salekhard hydrological stations) [66]. Approximately 80% of SPM is supplied during the summer season [67]. It is found that the most part of the SPM (80–90%) is deposited within the MFs of the rivers [29]. Coastal abrasion may also serve as an important source of the SPM, in addition to the river runoff [68].

The biogenic constituent of the SPM (phytoplankton and detritus) is subjected to seasonal changes exceeding in their scale the annual variation. This is explained by the fact that phytoplankton growth is firmly limited by the influx of photosynthetically available radiation and biogenic elements with the river runoff. The onset of the vegetation period depends on ice conditions in the sea. According to estimates of primary production, the Kara Sea represents an oligotrophic basin characterized by low phytoplankton biomass [4, 46]. The maximum rate of phytoplankton growth in the inner shelf occured in August and the beginning of September. The phytoplankton bloom is usually related to development of diatom and green algae and, to lesser extent, cyanobacteria communities [36, 46].

MATERIALS AND METHODS

The samples for this study were collected in two cruises of the R/V *Akademik Mstislav Keldysh*: Cruise 54 (September 5–October 7, 2007) in the western part of the Kara Sea and Cruise 59 (September 10–30, 2011) in its eastern part (Fig. 1). In our paper, particular attention is paid to results obtained along two submeridional transects: Ob and Yenisei. In these cruises, the SPM was studied at 21 and 22 stations, respectively (in total, 158 samples collected by Niskin bottles). Additional samples were taken by bucket at sea surface in the course of the vessel (in total, 33 samples). The samples were studied in line with the single program and methods.

Methods of sampling and analysis of the SPM. At oceanographic stations, water samples were taken by the Rosette sampler equipped with 10 and 5 L bottles. The sampling layers were selected on the basis of results obtained during the preliminary vertical sounding of optical and hydrophysical parameters [2, 15]. The preliminary treatment of the samples was performed onboard the vessel in the laboratory. It included water filtration by a vacuum through membrane and fiberglass filters and examination with the particle counting and sizing analyzer—Coulter counter®.

For determining the mass concentration of the SPM (mg/L), water samples were filtered using the standard method under the vacuum of 400 mbar through membrane nuclear filters (pore diameter 0.45 μm, filter diameter 47 mm, production of the Joint Institute of Nuclear Research, Dubna, Russia) [20, 31]. Each sample (~5 L) was simultaneously filtered through three and more filters (~580 SPM samples on the filters). The SPM concentration was measured by weighting filters with accuracy of ±0.01 mg and correlating it with the volume of filtered water.

For determining concentrations of POC and its isotopic composition ($\delta^{13}C_{POC}$), the water samples were filtered by a vacuum of 200 mbar through GF/F fiberglass filters produced by the Whatman Company (filter diameter 47 mm, effective pore diameters 0.7 μm) ignited at $t = 250$°C. The methods used for determining the concentration and isotopic composition of carbon are discussed in [17, 27]. In total, ~90 samples were analyzed.

The volumetric SPM concentration was measured using the Multisizer™ 3 analyzer (Coulter counter®) designed by the Beckman Coulter Company, USA (ISO 13319) [52]. The analyzer was calibrated on board using a standard latex suspension with a nominal particle size of 5 μm (Coulter® CC Size Standard L5). The measured size of particles varied from 2 to 60 μm. The method for measuring is discussed in [20–22].

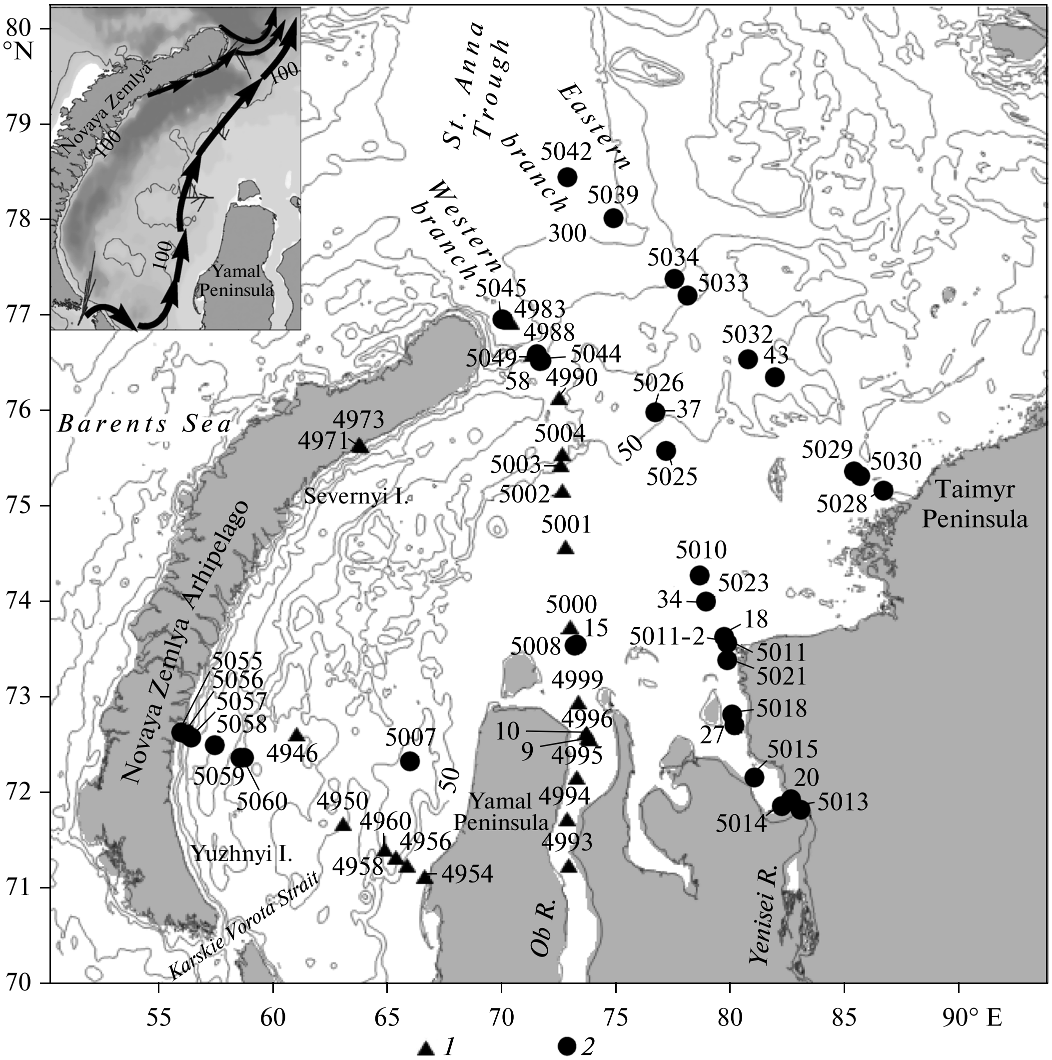


Fig. 1. Schematic map of SPM sampling sites in the Kara Sea: (*1*) September 2007, (*2*) September 2011. In the inset, arrows show circulation patterns in the upper 100-m-thick water layer in the southwestern part of the sea after [15]; the solid line designates the 100-m isobath.

The mass and volumetric SPM concentrations exhibit a linear correlation that is more distinct in samples with the incresed share of pelitic mineral particles (Fig. 2). The joint measurement of the light attenuation coefficient (*C*) derived from the PUM-A transparency measurer data and concentration of the SPM made it possible to establish correlation between these parameters (Table 1).

Microimages of the SPM were obtained at the VEGA-3sem TESCAN scanning electron microscope (Czechia) equipped with the X-ray spectral microprobe (Oxford INCA Energy 350, Great Britain). The Si and Al content in the SPM were determined by the photometric method in line with the procedure developed in the Institute of Geochemistry and Analytical Chemistry of the Russian Academy of Sciences [9] and modified for small weighed portions at the filter by A.B. Isaeva and V.N. Lukashin in the IO RAS. The accuracy of this method is ±15%. In total, 89 samples were analyzed.

Satellite-based observations. The data on the satellite-based MODIS-Aqua color scanner (http:// oceancolor.gsfc.nasa.gov/) were used for calculating SPM concentrations in the surface optically transparent water layer [57]. For this purpose, regional calculation algorithms were developed [3, 59]. Pairs of simultaneous measurements of the sea brightness coefficient and on board measurements of SPM concentrations in September 2007 and 2011 were selected for calculations. On the basis of data obtained for two spectral channels (531 and 551 nm), the coefficient of backward scatter by suspended particles (b_{bp}, m^{-1}) was calculated for these pairs. The algorithms used for calculating mass concentrations of the SPM (M_{SPM}) are based on the regressive correlation between M_{SPM} and b_{bp}. The color images of sea

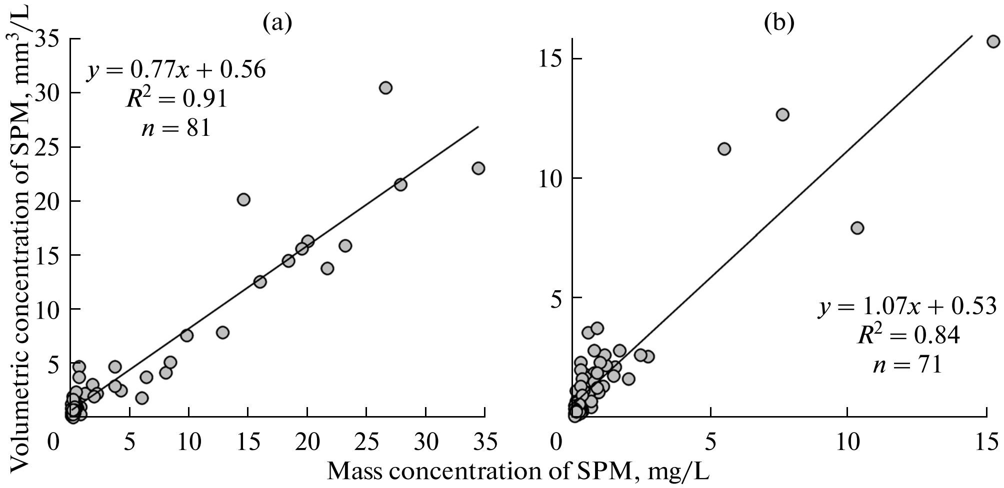


Fig. 2. Relationship between volumetric and mass concentrations of SPM in the Kara Sea according to the data obtained in expeditions of 2007 (a) and 2011 (b).

surface monthly average SPM distributions in September 2007 and 2011, with 1.1 × 1.1 km spatial averaging, are given in the digital atlas (http://optics.ocean.ru) were obtained using the following expressions [59]: $M_{SPM} = 99\ b_{bp}$, $R^2 = 0.55$, $n =$ 162 pairs of simultaneous measurements of b_{bp} values and SPM concentrations.

RESULTS AND DISCUSSION

Table 2 presents the measured parameters of the SPM at different layers of the water column. The SPM concentration in the active layer of the Kara Sea (~1.2–1.3 mg/L on average for 2007 and 2011) appeared to be close to the corresponding value in the White (~1.4 mg/L on average for 2003–2010) and Laptev (~1.7 mg/L on average for 2003, 2004, 2007, and 2008) seas [6, 13]. Such a similarity is explained by the fact that all these Arctic seas are subjected to strong influence of the river runoff, which plays a controlling role in the formation and spatial distribution of marine SPM.

Spatial distribution of the SPM concentrations in the surface layer. The satellite images of sea surface monthly average SPM distribution (September 2007 and 2011) demonstrate that the increased water turbidity (>1 mg/L) is confined to the southern coastal areas of the Kara Sea including Ob and Yenisei MFs [3, 59]. According to our data, the SPM concentrations in the desalinated water layer of the estuaries and adjacent shallow water areas were higher than the values obtained by other authors in the 1980s–1990s [6, 34, 51]. For example, the average SPM concentration in the desalinated water layer of the Ob Estuary (salinity 3–10 psu) was as high as 16 mg/L (September 2007). According to previous measurements, it did not exceed 5 mg/L in September 1997 [33] and 10 mg/L in August–September 2001 [54]. Some authors noted a tendency for the increase in the SPM concentrations in coastal areas of the Kara, Laptev, and East Siberian seas in the period of 1956–2008 [6].

Table 1. Equations of regression correlating the light attenuation coefficient (C) with mass (M_{SPM}) and volumetric (V_{SPM}) concentrations of SPM

Sea	Year and season	Equation of regression	n	R^2	Source
Kara	2007 September–October	$M_{SPM} = 0.83C + 0.03$	53	0.97	[3]
		$V_{SPM} = 1.02C + 0.49$	50	0.86	This work
	2011 September	$M_{SPM} = 0.91C - 0.13$	64	0.90	This work
		$V_{SPM} = 1.20C + 0.23$	96	0.75	This work
	1993, 2007 September–October	$M_{SPM} = 0.83C - 0.06$	156	0.93	[3]
Barents Kara Laptev	1991, 1993, 1998, 2007 August–October	$M_{SPM} = 0.837C - 0.04$	285	0.92	[3]

Table 2. SPM concentrations and light attenuation coefficient (*C*) in the Kara Sea at oceanographic stations in Cruises 54 and 59 of the R/V *Akademik Mstislav Keldysh*

Station	Coordinates		Water depth, m	Layer, m	Salinity, psu	SPM		C, m^{-1}
	N	E				mg/L	mm^3/L	
Cruise 54 of the R/V *Akademik Mstislav Keldysh*, September–October, 2007								
4946	72°00.0′	61°00.0′	153	0	28.02	0.34	1.21	0.42
				20	32.14	0.18	0.32	0.26
				30	33.2	0.17	0.30	0.31
				70	34.18	0.34	0.47	0.15
4950	71°40.9′	63°00.3′	118	0	22.45	0.27	0.93	0.5
				9	25.92	0.33	1.10	0.45
				30	33.42	0.12	0.29	0.13
				50	33.78	0.18	0.18	0.14
				71	34.14	0.28	0.14	–
				115	34.45	0.27	0.34	–
4954	71°07.8′	66°37.0′	16	1	33.49	9.77	7.58	7.89
				14	33.41	15.95	12.53	7.99
4956	71°15.0′	65°50.2′	35	0	30.93	0.64	0.92	0.36
				14	32.26	0.32	0.94	0.34
				21	32.87	0.25	0.81	0.38
				25	33.14	1.67	2.31	1.43
				32	33.19	1.92	3.05	2.19
4958	71°19.6′	65°19.0′	117	0	28.88	0.42	0.88	0.52
				15	33.11	0.3	0.51	0.29
				26	33.71	0.21	0.47	0.22
				55	34.01	0.57	0.70	0.63
				110	34.39	0.92	1.08	0.6
4960	71°24.5′	64°50.5′	118	0	27.83	0.6	0.87	1.1
				10	32.86	–	0.77	–
				18	33.29	0.2	0.30	0.12
				29	33.49	0.13	1.18	0.1
				60	34.17	0.09	0.82	0.16
				109	34.46	0.3	1.99	0.5
4993	71°14.9′	72°51.6′	23	2,5	0.05	23.13	15.86	8.5
				21	0.05	20.07	16.20	8.2
4994	71°44.0′	72°47.3′	16	1	0.60	34.37	23.03	8.84
				15	0.87	80.8	42.97	9.31
4995	72°10.0′	73°14.4′	14	2	3.55	21.68	13.78	9.74
				11	8.69	27.85	21.56	9.55
4996	72°34.2′	73°49.3′	16	1	5.95	19.57	15.58	8.78
				2	13.47	3.82	2.85	8.9
				15	24.43	14.65	20.08	8.88
9	72°35.3′	73°44.5′	21	0	5.50	18.33	14.41	–
10	72°38.7′	73°40.8′	21	0	8.64	12.8	7.91	–
4999	72°57.2′	73°17.1′	26	1	9.32	6.47	3.75	7.66
4999	72°57.2′	73°17.1′	26	6	21.22	1.97	1.91	1.41
				24	29.51	26.58	30.43	9.58
5000	73°45.0′	72°56.6′	23	1	19.79	0.4	1.17	0.81
				18	31.78	6.08	1.83	8.52
				22	32.05	8.09	4.08	9.01

Table 2. (Contd.)

Station	Coordinates		Water depth, m	Layer, m	Salinity, psu	SPM		C, m^{-1}
	N	E				mg/L	mm^3/L	
5001	74°35.0′	72°45.5′	24	2	20.65	0.32	1.73	0.74
				12	27.7	0.19	0.42	2.42
				23	32.03	8.4	5.07	4.16
5002	75°10.1′	72°37.0′	29	2	18.82	0.56	2.30	0.82
				9	19.09	0.44	1.70	0.78
				25	32.16	3.83	4.74	3.57
5003	75°26.4′	72°31.9′	55	0	19.04	0.55	1.89	0.86
				10	29.00	0.3	0.97	0.78
				14	32.53	0.7	2.39	0.6
				47	33.73	0.78	3.68	1.26
5004	75°33.2′	72°31.3′	110	0	18.54	0.43	0.94	0.93
				15	32.02	0.2	0.40	0.28
				40	33.62	0.27	0.34	0.39
				103	34.03	0.37	0.75	–
4983	76°55.2′	70°16.2′	555	0	34.17	0.23	0.66	0.22
				40	34.43	0.35	0.56	0.25
				62	34.57	0.33	0.72	0.19
				200	34.76	0.18	0.31	–
				528	34.91	4.3	2.51	–
4988	76°35.3′	71°15.4′	183	0	33.95	0.32	0.36	0.3
				20	33.97	0.27	0.40	0.28
				37	34.05	0.25	0.45	0.26
				60	34.36	0.25	0.64	0.18
				102	34.64	0.3	0.33	0.24
				178	34.80	0.34	0.45	–
4990	76°09.0′	72°29.7′	114	0	26.24	0.48	0.89	0.58
				12	32.58	0.27	0.40	0.3
				24	33.37	0.23	0.39	0.14
				55	34.07	0.29	0.59	0.27
				78	34.18	0.24	0.34	0.31
				111	34.27	0.53	1.24	0.59
4971	75°39.9′	63°41.2′	173	0	16.02	1.25	2.16	–
				25	33.87	0.42	0.29	–
				50	34.24	0.33	1.13	–
				163	34.45	0.93	0.25	–
4973	75°39.0′	63°45.8′	32	0	16.68	2.32	2.26	–
Cruise 59 of the R/V *Akademik Mstislav Keldysh*, September 2011								
5007	72°20.4′	65°59.4′	138	1	16.45	0.43	0.83	1.21
				5	29.10	0.62	0.64	0.53
				20	32.37	0.16	0.14	0.15
5007	72°20.4′	65°59.4′	138	136	34.58		0.45	
5010	74°17.0′	78°37.3′	30	3	26.29	0.44	1.19	0.46
				5	26.31	0.31	0.84	0.36
				10	26.37	0.35	2.31	0.37
				20	31.04	0.58	3.58	0.89
				28	31.95	2.06	1.65	2.36
5011	73°33.4′	79°47.0′	36	3	27.95	0.59	1.16	0.69
				17	31.04	1.56	2.13	0.76
				35	32.43	2.75	2.58	3.16

Table 2. (Contd.)

Station	Coordinates		Water depth, m	Layer, m	Salinity, psu	SPM		C, m^{-1}
	N	E				mg/L	mm^3/L	
5013	73°33.4′	79°47.0′	30	1	0.06	2.55	–	4.05
				30	0.07	3.95	–	4.28
5014	71°52.1′	82°11.9′	9	1	0.05	2.93	–	4.83
				8	0.07	1.81	–	4.96
5015	72°10.1′	80°59.7′	14	3	0.30	2.73	–	4.35
				12	23.41	10.31	7.91	9.11
5018	72°49.0′	79°59.7′	22	3	20.57	1.15	1.3	2.73
				6	25.55	0.97	1.08	1.17
				14	28.37	1.53	1.76	2.16
				20	31.04	5.53	11.25	7.47
5011-2	73°34.5′	79°47.0′	38	5	12.52	1.27	2.21	–
				12	29.94	0.51	1.78	–
				25	31.30	1.19	2.65	–
				34	32.34	1.73	2.84	–
5021	73°23.9′	79°49.6′	34	1	17.12	1.04	2.34	1.42
				31	31.54	7.63	12.71	6.33
5023	74°01.0′	78°53.7′	32	2	17.68	0.82	1.86	2.50
				5	25.86	0.83	2.78	2.74
				22	31.88	1	5.17	1.21
				27	32.11	2.5	2.6	3.82
5025	75°35.1′	77°09.9′	47	2	22.94	0.47	1.67	0.57
				45	33.52	0.71	0.42	0.75
5026	75°59.9′	76°40.0′	63	2	24.22	0.34	2.01	0.48
				6	24.20	0.4	1.62	0.49
				20	32.85	0.16	1.14	0.22
				60	33.99	0.38	0.33	0.41
5028	75°10.0′	86°39.7′	40	2	18.19	0.82	1.53	1.24
				8	21.68	0.65	1.05	2.58
				20	31.86	0.19	0.41	0.28
				38	33.40	0.9	3.73	1.08
5029	75°21.9′	85°21.3′	53	2	29.14	0.24	0.41	0.26
				8	29.12	0.31	0.35	0.25
				51	33.71	0.92	1.85	1.01
5030	75°19.3′	85°38.1′	41	2	24.39	0.58	0.99	0.87
				3	25.96	0.71	0.67	2.38
				14	29.13	0.21	0.41	0.28
5030	75°19.3′	85°38.1′	41	37	33.29	0.9	1.23	0.62
5032	76°33.1′	80°44.8′	59	2	28.64	0.28	0.41	0.29
				16	30.67	0.29	0.46	1.03
				40	33.75	0.17	–	0.17
				56	34.05	0.42	1.12	0.59
5033	77°13.1′	78°05.1′	121	2	27.27	0.31	1.32	0.42
				9	27.55	0.37	0.95	0.41
				55	34.14	0.26	0.55	0.18
				119	34.41	0.36	0.24	0.37

Table 2. (Contd.)

Station	Coordinates		Water depth, m	Layer, m	Salinity, psu	SPM		C, m^{-1}
	N	E				mg/L	mm^3/L	
5034	77°23.2′	77°29.4′	221	2	31.12	0.26	0.73	0.39
				15	32.63	0.16	0.53	0.23
				110	34.72	0.22	0.16	0.17
				217	34.89	0.35	0.39	–
5039	78°01.2′	74°49.6′	358	2	31.59	0.16	0.66	0.26
				20	34.34	0.29	0.4	0.22
				150	34.85	0.31	0.19	–
				355	34.95	0.25	0.26	–
5042	78°28.0′	72°49.1′	464	2	32.09	0.15	0.45	0.28
				9	33.32	0.15	0.65	0.46
				35	34.40	0.13	0.49	0.23
				100	34.87	0.1	0.08	0.13
				290	34.86	0.12	0.15	–
				460	34.94	0.27	0.26	–
5044	76°32.2′	71°39.4′	152	2	24.12	0.35	0.97	–
				4	31.85	0.28	0.56	–
				110	34.59	0.12	0.2	–
				147	34.78	0.26	–	–
5045	76°58.4′	69°59.5′	529	7	33.70	0.13	0.39	0.46
				20	34.19	0.15	0.28	0.21
				100	34.85	0.13	0.71	0.14
				527	34.95	0.15	0.22	–
5049	76°35.7′	71°27.0′	182	4	26.88	–	0.57	–
				8	32.55	–	0.29	–
				25	33.98	–	0.14	–
				50	34.22	–	0.21	–
				80	34.42	–	0.37	–
				100	34.54	–	0.10	–
				150	34.70	–	0.18	–
				179	34.73	–	0.40	–
5055	72°38.4′	55°59.4′	46	1	30.76	–	1.44	0.41
				6	31.47	–	1.20	0.58
				15	33.02	–	0.85	0.25
				25	34.00	–	0.32	0.21
				35	34.23	–	0.16	0.19
				42	34.36	–	0.25	0.19
5055	72°38.4′	55°59.4′	46	50	34.39	–	0.21	0.20
5056	72°37.1′	56°10.3′	105	3	29.94	–	0.96	0.57
				6	30.05	–	0.79	0.65
				10	32.78	–	0.50	0.41
				20	33.80	–	0.53	0.32
				30	34.10	–	0.29	0.20
				50	34.32	–	0.16	0.21
				75	34.39	–	0.10	0.21
				106	34.50	–	0.21	0.23
5057	72°35.5′	56°23.9′	215	3	30.13	–	0.92	0.42
				5	30.08	–	0.79	0.43
				12	33.10	–	0.59	0.28

Table 2. (Contd.)

Station	Coordinates		Water depth, m	Layer, m	Salinity, psu	SPM		C, m^{-1}
	N	E				mg/L	mm^3/L	
				15	33.29	–	0.74	0.32
				20	33.86	–	0.63	0.36
				30	34.05	–	0.20	0.22
				50	34.23	–	0.16	0.22
				100	34.48	–	0.12	0.20
				209	34.63	–	0.36	–
5058	72°30.0′	57°25.1′	340	2	31.37	–	0.50	0.34
				10	31.95	–	0.58	0.31
				15	32.53	–	0.50	0.28
				30	33.99	–	0.26	0.20
				50	34.13	–	0.16	0.20
				70	34.33	–	0.16	0.19
				120	34.47	–	0.08	0.18
				200	34.59	–	0.16	–
				312	34.69	–	0.21	–
5059	72°22.0′	58°33.0′	195	1	32.26	–	0.52	–
				20	33.45	–	0.30	–
				30	34.08	–	0.18	–
				40	34.21	–	0.11	–
				50	34.30	–	0.11	–
				75	34.36	–	0.06	–
				100	34.47	–	0.13	–
				150	34.61	–	0.37	–
				192	34.61	–	0.45	–
5060	72°21.9′	58°40.9′	103	10	32.45	–	0.17	0.26
				14	32.45	–	0.25	0.26
				20	33.55	–	0.20	0.32
				25	33.99	–	0.21	0.17
				30	34.16	–	0.09	0.16
				50	34.37	–	0.05	0.18
				75	34.48	–	0.20	0.20
				103	34.48	–	0.21	0.23

In the open areas of the Kara Sea away from the sources of terrigenous material, the SPM concentrations became gradually uniform, usually amounting to 0.3–0.4 mg/L (Fig. 3). The most uniform patterns were characteristic for the SPM distribution in the western, so-called drainless area of the sea. Previously (September 1993), it was noted that its lowest concentrations (<0.5 mg/L) are also typical of the western part of the sea [51]. The river runoff in these areas is extremely low and bioproductivity of their waters is usually characterized by minimum values [4]. In 2007, the average SPM concentration in the desalinated layer of the sea (water salinity 15–20 psu) was approximately 0.5 mg/L.

Along the western coast of the Yamal Peninsula, the SPM concentration in the surface layer was as high as 9.8 mg/L (7.6 mm^3/L) due to coastal and bottom abrasion. The western coast of the Yamal composed of Upper Quaternary sandy–clayey deposits with fragments of formation ice is gradually abraded and retreats. For a period of 90 years (1914–2004), the shoreline retreated for 155–165 m [41]. Material from abraded cliffs enters the inshore area to decrease its depth gradually. According to our observations, the main share of terrigenous material is deposited in the coastal zone approximately 20 km wide partly reaching depths of 30–50 m.

At station 4950, where the mass concentration of the SPM was ~0.3 mg/L, its volumetric concentration above the halocline (depth of 9 m) was as high as 1.1 mm^3/L, which is explained by high biomass of phytoplankton [47].

A narrow band of waters with increased turbidity was observed along the coast of the Novaya Zemlya

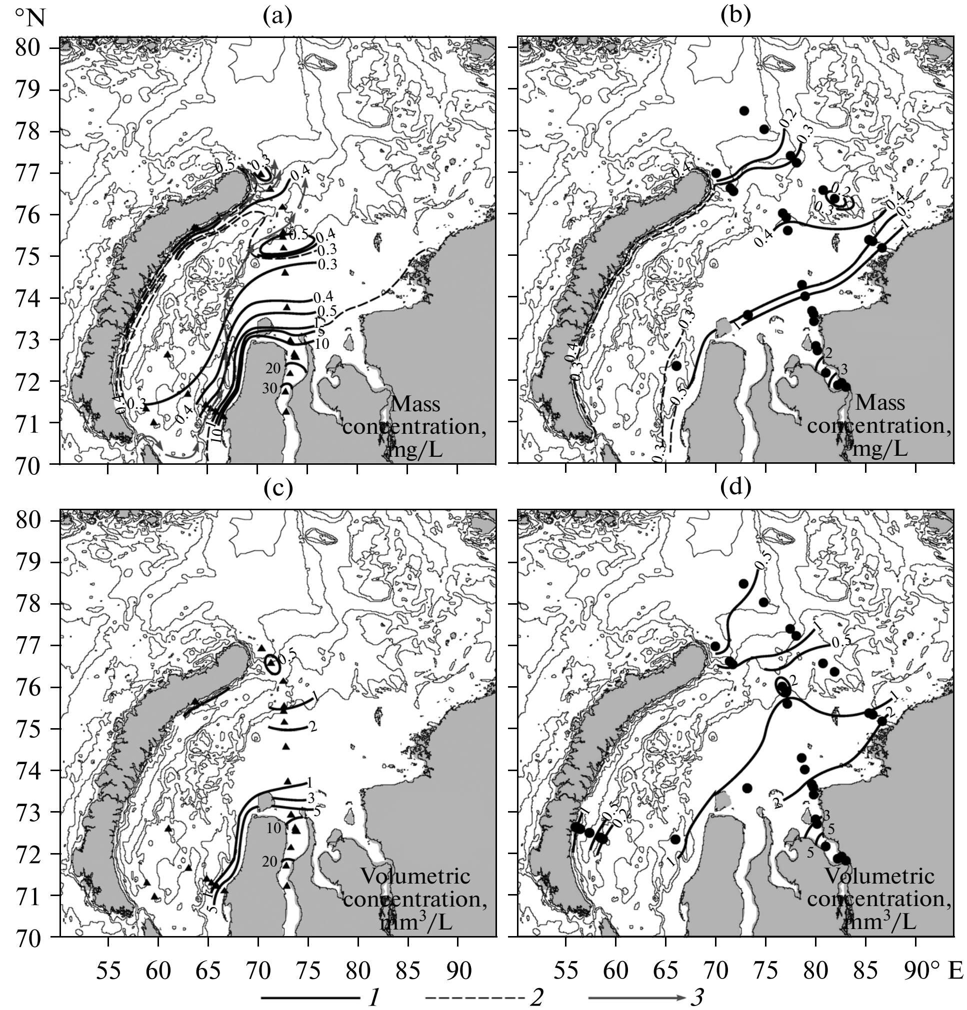


Fig. 3. Schematic map illustrating the distribution of the mass (mg/L) and volumetric (mm^3/L) concentrations of SPM in the surface water layer of the Kara Sea in September 2007 (a, c) and 2011 (b, d): (*1*) isolines according to field (onboard the vessel) measurements; (*2*) isolines of calculated concentrations derived from MODIS-Aqua data, after [5]; (*3*) schematic water circulation in the upper 100-m-thick layer according to observations in September 2007, after [15].

Archipelago. This phenomenon is most likely related to the discharge of ice-rafted material transported from the archipelago coast. According to field measurements, the SPM concentration in the surface layer of the Blagopoluchiya Bay (stations 4971, 4973) amounted to 1.3–2.3 mg/L (2.2 mm^3/L). In the semiclosed Ukromnaya Bight of this bay and in melt ice water, the SPM concentration was as high as 51.9 and 9.8 mg/L, respectively. The schematic maps illustrating the distribution of the SPM concentrations (Fig. 3) demonstrate clearly that ice-rafted material is deposited near the coast and provides no notable contribution to the SPM concentration in open areas of the western Kara Sea. Such pattern was first presented in papers [39, 63] where the fluxes of ice-rafted material near the Barents Sea coast of the archipelago were studied.

The satellite images obtained in 2007 for the northern extremity of the Novaya Zemlya Archipelago (Cape Zhelaniya) showed an area with the increased SPM concentration (>0.5 mg/L) related to the local coastal upwelling zone [3].

Marginal filter of the Ob River. According to field measurements in the desalinated part of the Ob Estuary (stations 4993, 4994; salinity 0.05–0.60 psu; gravitational step of the MF), the SPM concentration was as high as 34 mg/L (23 mm^3/L) and *C* value amounted to 8.8 m^{-1} with a Secchi disc visibility of ≤1 m. Despite a significant nutrients concentration [37] such the high SPM concentration was a limiting factor (with respect to light) for phytoplankton development. The largest share of primary production was formed in the surface 1-m-thick water layer (the thickness of the photic layer did not exceed 2.7 m) [46].

Within the frontal salinity zone (stations 4995–4999, salinity 3.5–10.0 psu), the SPM concentration decreased as the salinity increased 3–4 times: from

21.7 to 6.5 mg/L (from 13.8 to 3.8 mm^3/L) with C amounting to 9.7 m^{-1}). The SPM is removed from the active layer due to physicochemical and biogeochemical processes characteristic of the coagulation–sorption step of the MF [29] and supplied in the pycnocline (halocline) and near bottom layers. This process is accompanied by a decrease in abundance and diversity of freshwater algae with a simultaneous increase of these parameters for marine algae [46].

Areas with water salinity ranging from 5 to 9 psu were characterized by the relatively increased SPM concentrations (Fig. 4). Our researches and published data allow the conclusion that such increase concentrations were related to flocculation of the SPM and colloids [20, 34]. It was noted that these areas are characterized by maximum contents of aggregating spherical particles [34]. Our previous researches revealed that both freshwater and marine planktonic algae die off in waters with salinity ranging from 2 to 15 psu to yield free organic matter stimulating development of bacteria and floccules formation [21]. In our opinion, this phenomenon is universal, not regional. This is evident from model experiments demonstrating the influence of the microbial community on the stability of colloidal systems under increasing salinity, data on relative increase of SPM concentrations at salinity of 2–7‰ in the MF of rivers in the southeastern Baltic Sea and etc. [25, 35].

In the inner shelf north of the saline frontal zone (stations 5000 and 5001; water salinity 19.8–20.7 psu), the SPM concentrations reached the lowest values: 0.3–0.4 mg/L (1.7–1.2 mm^3/L); C = 0.7–0.8 m^{-1}. In this area, the correlation between the mass and volumetric concentrations was less distinct since contribution of terrigenous particles decreased against the increased the share of marine biogenic particles in the SPM.

Near the 50-m isobaths (stations 5002 and 5003) in waters with similar salinity (18.5–20.5 psu), the SPM concentration increased up to 0.6 mg/L (to 2.3 mm^3/L) due to marine phytoplankton, which is confirmed by the data in [46]. In this paper, it is noted that primary production values in the shallow shelf area (located north of the estuary frontal zone of the Ob River with water salinity of 3.5–10.0 psu) were several times higher as compared with the frontal zone being comparable with its values in the freshwater part of the estuary. This is determined by the significant increase in the water transparency (C up to 0.8 m^{-1}) due to the removal of the significant share of mineral SPM from the active layer and, correspondingly, sinking of the lower boundary of the photic zone up to 21 m. It was previously noted that the highest biological productivity is frequently observable beyond the outer boundary of the saline frontal zone: salinity of ≥20 psu corresponding to the biological step of the MF [12, 20, 33].

The rapid bottom deepening between the 50- and 150-m isobaths within the 8-mile-wide zone (stations 5003 and 5004; water salinity of ~19 psu) corresponds to a notable decrease in the SPM concentrations: from 0.6 to 0.4 mg/L (from 1.9 to 0.9 mm^3/L, respectively). The values of the volumetric concentration indicate indirectly the relatively sharp decrease in concentrations of marine phytoplankton in this area of the sea. This fact is confirmed by direct measurements: the lowest abundance and biomass of phytoplankton were observed at the northern station of the Ob section (station 5004) located in the outer shelf with depths of approximately 150 m [46].

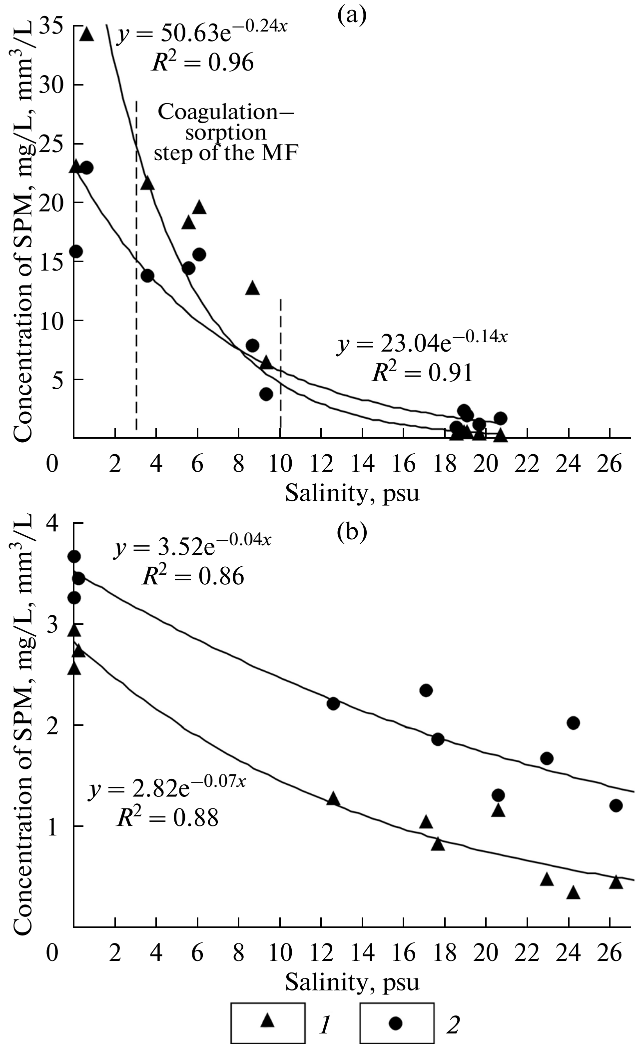


Fig. 4. Relationship between the distribution of the mass and volumetric concentrations of SPM and salinity in the surface water layer: (a) MF of the Ob River, 2007, (b) MF of the Yenisei River, 2011. (*1*) mass concentration of SPM, mg/L; (*2*) volumetric concentration of SPM, mm^3/L.

Marginal filter of the Yenisei River. In the fresh water area of the Yenisei River Estuary (stations 5013–5015), the SPM concentrations were as high as 2.6–2.9 mg/L (3–4 mm^3/L), which is approximately 12 times lower as compared with its values in fresh waters of the Ob Estuary (when maximum values are compared). Such a difference in the SPM concentrations was also reported in [34, 51, 54], although according to these data the difference between SPM concentrations in these rivers was not as large. The researches of 2007 revealed anomalous desalination of the surface water layer in the sea (up to <15 psu) due to the contribution of the waters of the Ob [14], which resulted in the enrichment of this layer with the SPM of river genesis.

The difference of between the sediment discharge of the Ob and Yenisei rivers is explained by the different compositions of rocks in drainage areas [29]. The drainage areas of these two rivers differ in their geological structure [19]. The drainage area of the Ob River comprises mainly the West Siberia Plain with a thick cover of sedimentary rocks and acid sod-podzolic (frequently peaty) soils subjected to river erosion. The Yenisei drainage area comprises the Middle Siberia Plateau, Sayan Mountains, and other structures of the Siberian Platform composed of crystalline rocks resistant to river erosion. In addition, eight large water storage reservoirs located in the upper reaches of the Yensei River likely reduce its sediment discharge, while the upper reaches of the Ob River host a single large water storage reservoir.

In the Yenisei Estuary, water salinity increased rapidly upstream: at stations 5018–5023, it ranged from 12.6 to 27.6 psu (depending of the tide phase) and SPM concentration varied from 1.3 to 0.6 mg/L (2.3 to 1.2 mm^3/L), respectively.

Our observations revealed that within isohalines of 12 and 20 psu, the SPM concentrations in the MF of the Yenisei River in 2011 were almost twice as high as in the MF of the Ob River in 2007 in areas with similar water salinity (Table 2). This was determined by close location of isohalines near the Yenisei Estuary, which formed a saline geochemical barrier. Previously, it was noted that SPM concentration values in the brackish-water part of the Yenisei Estuary are half as much as the Ob Estuary characterized by similar salinity values [34].

In 2011, the largest part of the Kara Sea was influenced by the Yenisei River runoff, which became mixed with Arctic water from the St. Anna Trough area and Barents Sea water from the Karskie Vorota area. The lens of desalinated water (salinity <19 psu) extended in the submeridional direction to occupy the northwestern part of the sea [13]. The influence of Ob River water was limited by the relatively small area adjacent to the Yamal Peninsula and immediately to the Ob Estuary. Such an annual variation of the river runoff and redistribution of Ob and Yenisei river waters in the Kara Sea predetermined annual variations in the influx and distribution of the SPM concentrations.

At the shallow-water shelf stations 5010 and 5023, the SPM concentration decreased to 0.4–0.5 mg/L (1.2–1.7 mm^3/L) and became more stable.

The area of the rapid bottom deepening between the 50- and 150-m isobaths (stations 5025, 5026) is marked by a notable decrease in mass SPM concentrations from 0.5 to 0.3 mg/L and, in contrast, an increase in its volumetric concentrations from 1.7 to 2.0 mm^3/L, respectively.

In MFs of the Ob and Yenisei rivers, SPM concentrations decreased exponentially depending on fresh and saline water mixing (Fig. 4). This phenomenon was reported in [10, 11, 20, 33]. In the mouth areas of large northern rivers (Lea, Yenisei, Pur, Taz, Ob, Severnaya Dvina), high gradients of the SPM concentration fall are revealed within the hydrological front at salinity of ≤20 psu [20, 33]. The biogeochemical processes in MFs of the Arctic rivers are similar in general. At the same time, these processes in the Ob and Yenisei river estuaries exhibit regular differences, which are distinctly reflected in curves of the exponential dependence (Fig. 4). These differences are determined by the different composition of sedimentary material, which is transported from provenances. Within the coagulation–sorption step of the MF, the samples deviate notably from the curve of the exponential dependence (dots are concentrated above the curve to form a convex bend), which is determined by specific biogeochemical processes characteristic of this step.

Unfortunately, no SPM samples were available for the area between isohalines of 2 and 11 psu corresponding to the coagulation–sorption step of the MF of the Yenisei River. The salinity gradient from 1 to 12 psu takes place over a short distance, which requires precision sampling from a small-size vessel. In [34], it is mentioned that the salinity interval between 4 and 8 psu is characterized by the increase of SPM concentrations related to flocculation of colloidal matter. Similar phenomenon was also observed in the MF of the Ob River between isohalines of 5 and 9 psu.

Thus, the distribution of SPM in the mixing zone of Ob and Yenisei river water with marine water is controlled by salinity and biota. The SPM concentrations decrease generally with salinity increase along the river–sea section. The main transformation of the SPM composition at the transition from estuary to shelf waters takes place within the saline frontal zone, the structure and position of which are subjected to seasonal and annual variations [15]. The differences in concentrations of SPM within these mixing zones were primarily determined by several following factors: (1) differences in the volume of the water and sediment discharge of the Ob and Yenisei rivers; (2) properties of rocks and soils in drainage areas of these rivers; (3) distribution of desalinated waters in the sea controlled by hydrometeorological factors. The topographic factor, i.e., rapid bottom deepening between the 50- and 100-m isobaths is responsible for the formation of the front and controls the concentration of SPM in the upper water layer of the outer part of the MF. According to [15, 23], the deep streams of main currents in the Kara Sea were located between isobaths of 50 and 100 m. The transition zones between different water masses coincide with the main currents that clearly reflected our data on the distribution of the SPM concentrations.

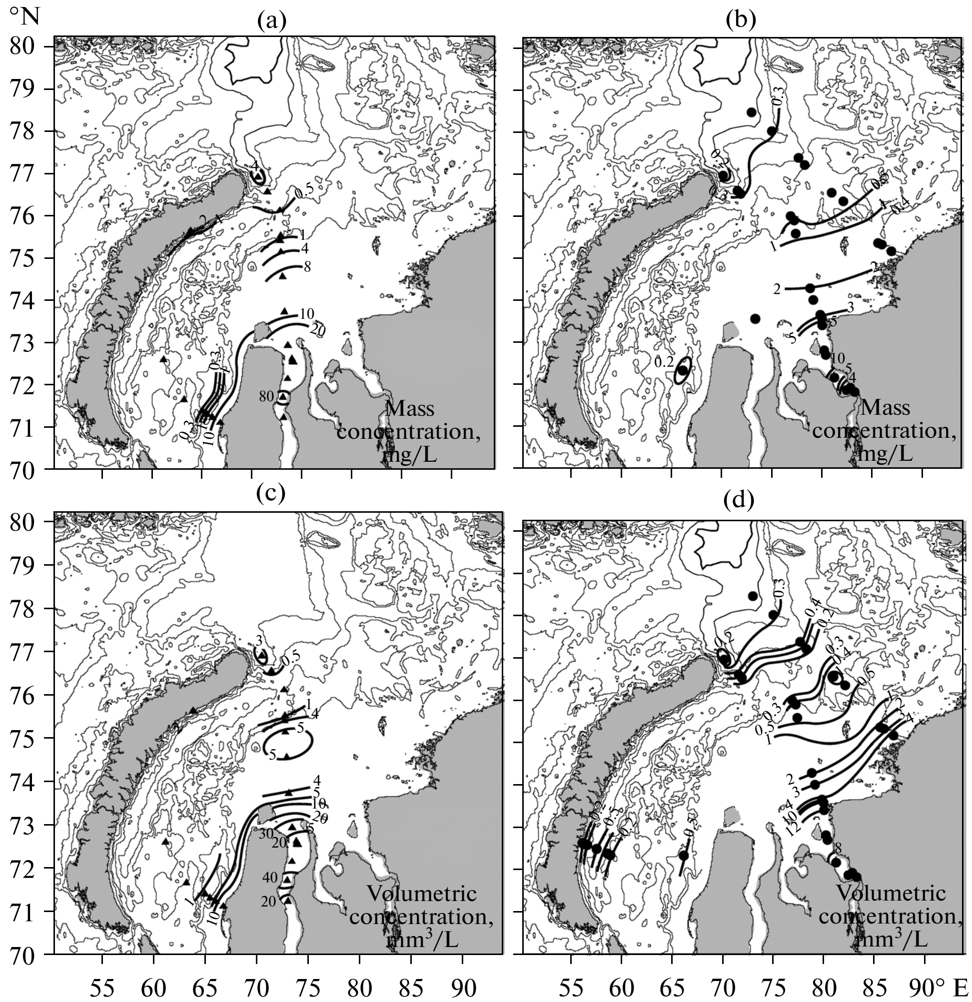


Fig. 5. Schematic map illustrating the distribution of mass (mg/L) and volumetric (mm^3/L) concentrations of SPM in the near bottom water layer of the Kara Sea in September 2007 (a, c) and 2011 (b, d).

Spatial distribution of SPM in the near bottom layer. As a whole, the vertical distribution of SPM was characterized by a three-layer structure: upper (active) layer above the pycnocline with the increased SPM concentrations; (2) intermediate layer of more transparent water under the pycnocline; (3) near bottom nepheloid layer. The first data on the vertical distribution of SPM along the main cross-shelf transects are available in [3, 27, 58].

The highest SPM concentrations (≥10 mg/L) were characteristic of the near bottom layer in the Ob and Yenisei estuaries and Yamal shallow water area near the abraded coast (Fig. 5). SPM concentrations in the Ob Estuary were locally as high as 80 mg/L (40 mm^3/L).

In the Ob coastal waters and north of the latter, the SPM concentration in the nepheloid layer reached to 8 mg/L (up to 5 mm^3/L). In the Yenisei coastal waters and near the Taimyr Peninsula, its concentrations near the bottom varied from 3 to 1 mg/L (4–1 mm^3/L). Our data showed that the distribution of SPM concentrations in the near bottom layer at the Ob–Yenisei shallow water area is characterized by significant variability both in sublatitudinal and submeridional directions: the concentration values decreased in the S–N- and W–E-ward within the shallow-water zones.

The spatial distribution of the nepheloid layer in the sea is controlled by its bottom topography. In the northerly direction, the SPM concentration near the bottom decreased to become 1.0–0.5 mg/L between isobaths of 50 and 100 m.

At the outer shelf, the SPM concentration in the near bottom layer varied usually from 0.2 to 0.5 mg/L, except for station 4983 (western branch of the St. Anna Trough), where it amounted to the anomalously high value of 4.3 mg/L (2.5 mm^3/L) at depth of 528 m in 2007. In 2011, it was only 0.15 mg/L (0.2 mm^3/L) in this area at 529 m depth (station 5045). Such a multiple increase in water turbidity near the bottom in 2007 is probably caused by the influence of the landslide on the slopes of the St. Anna Trough. It is known that terrigenous material is transported from its source (Novaya

Zemlya) to the deep part of the trough (its western branch) by nepheloid and gravitational currents [24].

The bottom nepheloid layer was widespread in the Kara Sea, which was noted by different researchers [2, 3]. This layer was found everywhere in the river estuaries and inner shelf areas up to the isobath of 100 m. The SPM concentration in the nepheloid layer of the Kara Sea is characterized by irregular spatial distribution varying from ~1 to tens of mg/L and approaching to its values in the Laptev and East Siberian seas and being much higher as compared with the White and Barents seas [31, 39, 50].

Comparison the SPM concentrations and phytoplankton abundances. The wet phytoplankton biomass in the active layer of the Kara Sea measured in the first half of autumn varied from 60 to 1600 μg/L [46, 47].

The indicative comparison between phytoplankton abundances presented in units of the wet biomass and concentrations of SPM (dry mass in 1 mL of water) revealed that the phytoplankton share in SPM in the Ob River estuary (stations 4993–4999) was usually below 5–6% increasing up to 50–75% (stations 5000, 5001) in the inner shelf, where the phytoplankton community was dominated by autotrophic dinoflagellate and diatom algae such as, for example, *Chaetoceros gracilis* (up to 57 and 42%, respectively, from total phytoplankton abundance). Closer to the wide frontal zone at the boundary between the inner and outer shelf (stations 5002–5004), the phytoplankton share in the mass SPM concentration decreased to 20–30%. The increase in the share of dinoflagellates in the total biomass of phytoplankton (up to 81%) was accompanied by the decrease in their contents in the dry mass of the SPM. Dinoflagellates with well-developed shells contain much water in their cells, which is lost during heating. The comparison of the wet phytoplankton biomass and dry mass concentrations of SPM may be useful when the species composition of dominant algae is taken into consideration.

Analogous comparison at the Yenisei profile showed that in the freshwater part, the fraction of raw phytoplankton biomass in the mass concentration of the suspension reached 40–70% in the photic layer (stations 5013–5015). To the north (stations 5018–5023), it did not exceed 25%. On a significant part of the middle shelf (stations 5010–5026), where the marine complex of phytoplankton dominated, its fraction in the suspension was 50–70% or more.

Beyond the outer shelf, the share of the wet phytoplankton biomass in the SPM was usually 60–80% and more. Such an increase in the share of phytoplankton in the SPM is consistent with the tendency for reduction of the terrigenous material in the latter away from the Ob and Yenisei estuaries.

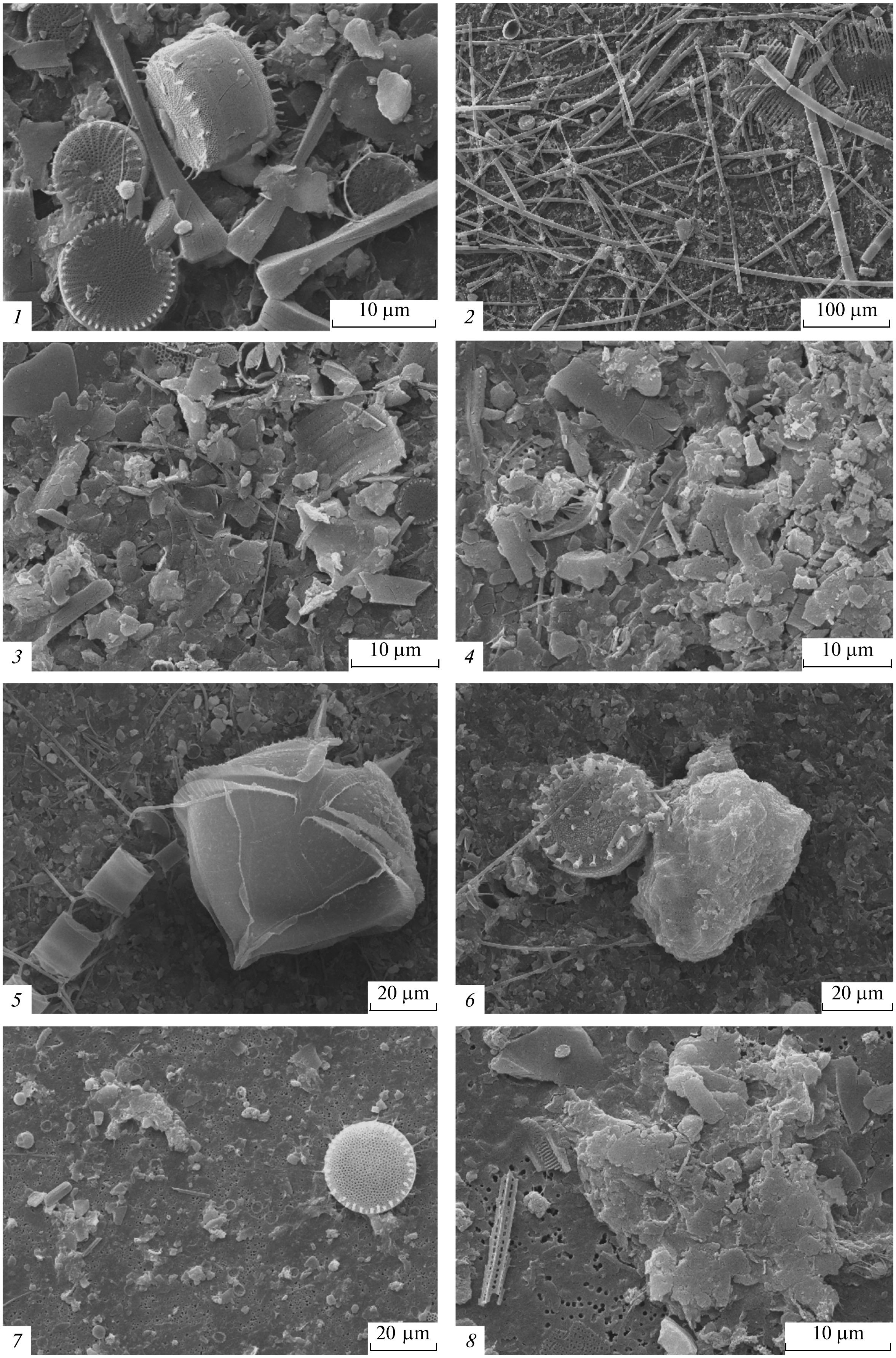
The indicative comparison of phytoplankton abundances presented in biovolume units (mm^3/L) with the volumetric concentrations of the SPM (fraction 2–60 μm) revealed that the phytoplankton share never exceeded 10% (station 4999) within the saline frontal zone of the Ob River and reached to 50% (station 5018) in the Yenisei River frontal zone. Northward of the saline frontal zone, it was as high as 10–25 and 60–76% along the Ob (station 5010) and Yenisei (station 5025) sections, respectively.

In the Yamal section, the phytoplankton share in the volumetric concentration of the SPM exceeded locally 60–90% (stations 4958, 4960, 4950). This area is marked by high phytoplankton biomass values, up to 1.06 gC/m^2 (Station 4950) [46].

The estuaries and shallow water shelf areas influenced by wave and tide current activity demonstrate intense mixing of the near bottom water layer and resuspension the upper layer of bottom sediments, which prevent the deposition of suspended terrigenous and biogenic particles. The microimages of these particles are shown in Figure 6. The sinking phytoplankton is involved by bottom currents into the lateral flow in the nepheloid layer. Water salinity in this layer is always higher (≥30 psu) as compared with that in the upper desalinated layer (≤15–25 psu) since the heavy saline water column is covered by lighter desalinate water of river origin. The near bottom layer is enriched both with mineral particles and POC. The POC concentration near the bottom is frequently close to that in the photic layer [1, 27]. Figure 6 demonstrates that among biogenic particles in the near bottom layer were found assemblage of single cells and colonies of diatom algae in the freshwater part of the Yenisei Estuary (*1, 2*), were prevailed debris of algae in the frontal zone (*3, 4*), and were presented single cells, colonies, and detritus of marine algae belonging to different classes in the shelf areas (*5, 6*). Previously, it was noted that freshwater algae of class Chlorophiceae occur among marine palynomorphs in bottom sediments practically everywhere in the Kara Sea [61].

Carbon isotope composition. The POC concentrations in the surface layer decreased from the estuary toward the outer shelf from 1400 and 407 μg/L to 110 and 66 μg/L in the Ob and Yenisei sections, respectively [1, 27]. In contrast, its share in the SPM increased in the same direction mostly due to preferential deposition of mineral particles at different steps

Fig. 6. Microimages of SPM samples from the near bottom water layer: (*1*) *Cyclotella* sp., *Aulacoseira distans*, *Asterionella formosa*, mineral particles; (*2*) *Fragilariopsis crotonensis, Aulacoseira* sp., mineral particles, Station 5013, layer 30 m; (*3*, 4) detritus and mineral particles, Station 5018, 20 m; (*5*) *Protoperidinium pallidum*, *Chaetoceros compressus*, *Ch. gracilis*, mineral particles; (6) *Talassiosira nordenskioeldii*, globular organic–mineral aggregate, mineral particles, detritus, Station 5010, 28 m; (*7, 8*) centric diatom, detritus, mineral particles, aggregate, organic film in the filter surface, Station 5045, 527 m.


1
10 µm
2
100 µm
3
10 µm
4
10 µm
5
20 µm
6
20 µm
7
20 µm
8
10 µm

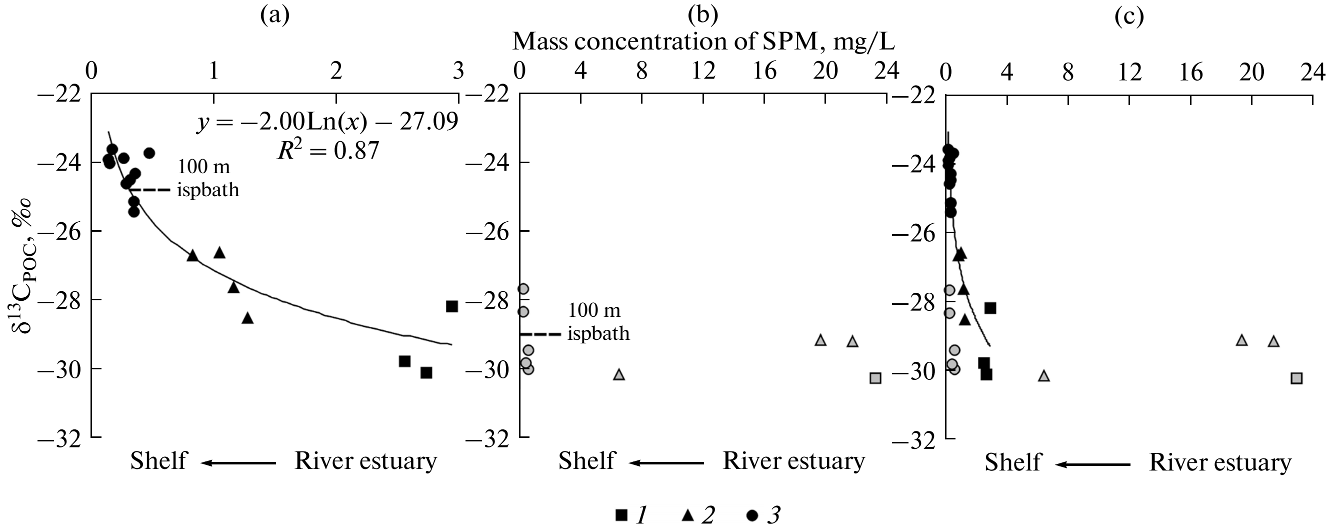


Fig. 7. Relationship between $\delta^{13}C_{POC}$ values and mass concentrations of SPM in the surface desalinated layer of the sea: (a) Yenisei section, September 2011, (b) Ob section, September 2007, (c) the data on the Yenisei and Ob sections. (*1*) desalinated part of estuaries (water salinity 0.05–0.50 psu); (*2*) estuaries and shelf to depths of 30–50 m; (*3*) shelf, depth >30–50 m.

of the MF and enrichment with newly formed autochthonous organic matter.

The $\delta^{13}C_{POC}$ values allow the proportions between terrigenous (allochthonous) and phytoplanktonogenic (autochthonous) organic matter in marine SPM to be estimated more careful [27]. The isotope composition of POC related with the SPM concentration (Fig. 7). The maximum concentrations of SPM are

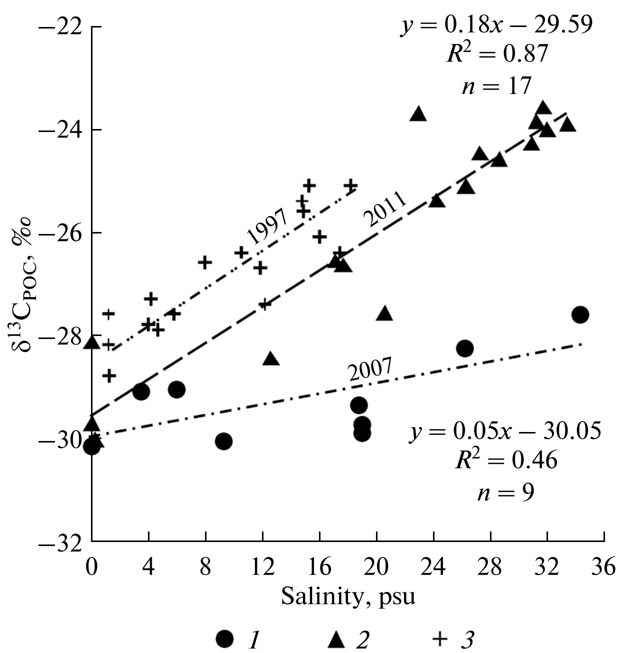


Fig. 8. Relationship between $\delta^{13}C_{POC}$ values and salinity in the surface water layer: (*1*) September 2007, according to [43], (*2*) September 2011, according to [27], (*3*) September 1997, according to [18].

found for river estuaries, where POC is mostly terrigenous: $\delta^{13}C$ values amount to –30.2 and –30.1‰ in the Ob and Yenisei estuaries with water salinity of 0.05 psu, respectively. It is known that the isotopic values range from –30 to –25‰ and from –23 to –19‰ for terrigenous and marine planktonogenic C_{org}, respectively [7, 53].

As a whole, our data confirm observations that the share of marine (phytoplanktonogenic) organic matter in the composition of POC increases away from the coast toward the outer shelf, which makes the $\delta^{13}C_{POC}$ values to heavier in the same direction [8, 27, 28, 56, 62]. At the same time, the $\delta^{13}C_{POC}$ values varied from –30.18‰ in the Ob estuary to –27.6...–24.8‰ near the northern extremity of Novaya Zemlya Island in the surface and bottom water layers, respectively (Station 4983) in 2007 (Fig. 8). Anomalous desalination of the surface water layer due to the influx of Ob water (~40 thou. km^2 in size and 10 m thick) revealed in 2007 resulted in the significantly lightened isotopic composition of POC through most of the sea as compared with our data of 2011 and data in [17, 18].

Our data confirm the previously revealed relationship between the enrichment of POC with its heavy isotope and the increase of salinity [17, 18, 28, 43] (Fig. 8). The reliable linear correlation (R^2 = 0.87, n = 17) between these parameters was found in September 2011 and less notable one in September 2007 (R^2 = 0.46, n = 9) after the summer period of extreme temperature and salinity values in the surface layer [4].

In the frontal zone between the isobaths of 50 and 100 m, the $\delta^{13}C_{POC}$ values in surface water varied from –29.9‰ at station 5003 to –29.8‰ at station 5004 along the Ob section (2007) at water salinity of ~19 psu and from –23.7‰ at station 5025 to –25.4‰ at station 5026 along the Yenisei section (2011) at salinity of 23–24 psu. Unlike in the Yenisei section, in the composition of organic matter at all the stations of the Ob section, except for the northernmost station 4983 dominated isotopically light (–28.0 to –30.2‰) material transported from the land [43].

At closely spaced stations located beyond the outer shelf, it was revealed that the $\delta^{13}C_{POC}$ values in surface waters varied from –27.6‰ (station 4983, 2007) to –23.9‰ (station 5045, 2011) in different years. The mass concentration of SPM at these stations varied as well: from 0.23 to 0.13 mg/L, respectively. In 2007, the area located near the northern coast of Novaya Zemlya with elevated SPM concentrations was under influence of cold waters related to local upwelling and, likely, melt water from the island [3]. In 2011, no upwelling was observable and station 5045 was in the stream of more warm Atlantic waters (temperature distribution map is available in the digital atlas at http://optics.ocean.ru). The SPM concentrations in the western branch of the St. Anna Trough reflect the hydrological situation during the sampling [58, 59].

Elemental composition of mineral SPM (according to data by microprobe and photometric analyses). According to data by the microprobe X-ray spectral analysis, terrigenous particles were dominated by quartz and aluminosilicates. Our and other [34, 55] researches demonstrated that aluminosilicates were characterized by different contents of accessory chemical elements. Aluminosilicate particles in SPM of the Kara Sea exhibit high X-ray intensity for some elements such as Si, Al, K, Fe, Mn, Mg, Na, Ca, Ti, and, occasionally, P and S. On the basis of all these data, several groups may be distinguished among defined aluminosilicates: (1) "pure"; (2) with low contents of accessory elements; (3) enriched with Fe; (4) enriched together with Fe and Mn (most frequently, aggregates, not individual particles); (5) containing Ti, in addition to other elements; (6) containing Ca, in addition to other elements.

The presence of K (usually up to 15 wt %) in the SPM is most characteristic of the western part of the sea and the Ob Estuary. It has been shown previously that the Ob River represents a powerful supplier of K feldspars to sediments of the Kara Sea [26, 64].

Aluminosilicates enriched with Fe (2–7%, less commonly, to 15 wt %) occured in SPM almost everywhere (stations 5007, 5013, 5033, and others). It is established that SPM in the Yenisei Estuary contains particles, which are enriched with Ca (up to 6 wt %) and P, in addition to Si and Al. Such a feature was also mentioned in [27, 34]. Our data confirmed observations that the SPM of the Yenisei River was more enriched with Ti as compared with its counterpart from the Ob River, which is determined by differences in the composition of rocks in drainage areas of these rivers [34, 60].

The enrichment of the SPM with Mn was likely explained by sorption and precipitation of Mn ions

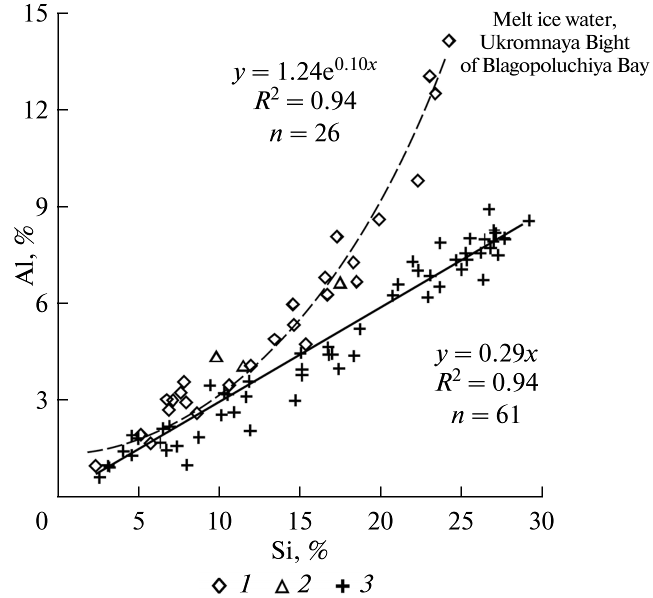


Fig. 9. Relationships between the Al and Si concentrations in SPM in September 2007. Sampling sites: (*1*) near Novaya Zemlya and southern part of the St. Anna Trough (western branch), (*2*) the frontal zone of the Yamal Current (position of the front after [15]), (*3*) western part of the sea.

together with colloids of Fe hydroxides and their additional formation [34].

The content of Al in the SPM serves as a reliable indicator of its terrigenous constituents [32]. According to the data by photometric analysis, the Al concentration in the Ob and Yenisei estuaries averaged 7.4% (13 samples), which was close to the published data on the composition of river SPM: 6.2% [32], 6.3% [34], 7.0% [22], and 6.0% [20]. This value was also similar with that obtained for sedimentary rocks of continents: 8.58% [42]. In the river estuaries and near the Yamal Peninsula, the calculated (Al × 100/8.58 [32]) share of terrigenous SPM was 70–95%.

In the open part of the Kara Sea, the Al concentration averaged 4% (66 samples) being practically always exceeded 1–2%, which indicated the absolute prevalence of terrigenous material in the SPM composition. For example, the Al share in the SPM varied from 0.5 to 3.3% [20, 21] and from 0.5 to 1.0% [12] in the open parts of the White and Baltic seas, respectively.

It is found that SPM of the Kara Sea (including the Ob and Yenisei estuaries) is characterized by a strong correlation between the Al and Si content (Fig. 9). The linear correlation between these elements was also revealed for the samples from estuaries and largest part of the sea, i.e., it was characteristic of terrigenous material, which was transported by rivers. The power correlation was typical of the samples from sea areas adjacent to Novaya Zemlya, i.e., terrigenous material transported from the archipelago by melt water and glaciers. These material are depleted in Si relative to Al: the Si enrichment coefficient is 0.6–0.9 (EC = $(\text{element}/\text{Al})_{SPM}/(\text{element}/\text{Al})_{clay}$).

Indicating the Si/Al values, the influence of material transported from Novaya Zemlya was limited to waters immediately adjacent to the archipelago coast. Near the northern extremity of Novaya Zemlya, this material may be distributed by the East Novaya Zemlya Current in the northeasterly direction from ~76°30′ N. Only a small share of this material reached southerly areas. Station 4990 (76°09′ N) was influenced by terrigenous material transported mostly by rivers and only partly by material originating in the archipelago. The Si/Al value averages 3.51 for marine SPM beyond the influence of material from Novaya Zemlya (i.e., in the largest part of the sea) and was 3.46 in the river SPM of the Ob Estuary, which was 87 close to this parameter in continental clays and shales (3.06) [42]. This fact indicates that the structure of clayey aluminosilicate particles during their transport from the drainage area and its distribution in the sea is insignificantly transformed. The notable enrichment of SPM with Si relative to Al (EC to 2.6, station 4950) was explained by the increased share of amorphous silica, which was indirectly evident from the increased biomass of diatom algae.

CONCLUSIONS

The distribution of SPM concentrations in the Kara Sea was primarily characterized by the latitudinal zonality observable from the Ob–Yenisei shallow water area up to the foot of continental slope. The processes of cross-shelf transport of the SPM (and the so-called cross-shelf zonality [49]) were topographically controlled.

Increased concentrations of the suspension (more than 5 mg/L) are localized, as a rule, in the near-coastal zone (near river estuaries and scarps), where a complex structure of currents [15] suspending flows and nepheloid layers is formed.

The composition and concentration of the SPM in the Ob and Yenisei waters were substantially different due to different rocks compositions in drainage areas of these rivers. The influx and distribution of transformed river SPM in the Kara Sea depended to significant extent on hydrometeorological conditions in the Arctic Ocean.

Our researches revealed that the SPM concentrations in the freshwater part of the Ob Estuary were ~10–12 times higher in 2007 than its values in the Yenisei Estuary in 2011. The SPM composition in the estuary was dominated by mineral particles, although the share of phytoplankton in its total concentration in the Yenisei River was approximately 10 times higher than that in the Ob River.

The mixing of fresh and saline waters in the MF of the Ob and Yenisei rivers was accompanied by the exponential decrease in SPM concentrations. The distribution of the SPM concentrations in the surface water layer over the inner shelf is controlled by its salinity. Main transformation of the SPM composition at the transition from estuary to shelf waters takes place within the saline frontal zone, the structure and position of which are subjected to seasonal and annual variations.

Our data on the isotopic composition of POC reflect the previously established regularity along the river–sea section: closer to the outer shelf, the share of marine (phytoplanktonogenic) organic matter increased in POC, which made the $\delta^{13}C_{POC}$ values heavier. The important role in the formation of this isotopic shift belongs to water salinity. The anomalous desalination of the surface water layer of the sea (due to contribution of Ob water) in 2007 resulted in significant lightening of the POC isotopic composition in the western part of the Kara Sea up to the southern periphery of the St. Anna Trough.

The bottom topography (depth changes between the isobaths of 50 and 100 m, where streams of main currents are located [15]), determined the formation of the hydrological front that divided different water masses and controled, according to our data, the distribution of the SPM concentrations in the middle part of the shelf.

Material transported by melt water from eastern shores of the Novaya Zemlya Archipelago did not contribute much to the SPM concentration in the open areas of the Kara Sea. The SPM concentration in the examined bays of the eastern coast of Novaya Zemlya was as high as 1–3 mg/L. The distribution areas of material transported from the island were located immediately along its shores. The analysis of the SPM composition provided grounds for concluding that the latter may be transported from this source by the East Novaya Zemlya Current along Severnyi Island (for schematic map of currents, see Fig. 1). Near the northeastern extremity of the archipelago, the current deviated from the shore and transported SPM in the sublatitudinal, mostly northeasterly direction from ~76°30′ N along the southern periphery of the St. Anna Trough. The current interacted intensely with the surrounding waters [15] to mix terrigenous SPM from different sources: island material from Novaya Zemlya and continental material transported by rivers from West and East Siberia. Nevertheless, the SPM practically in all samples taken at the shelf and north of it (up to the isobaths of ~200–500 m) contained the terrigenous constituent: mineral particles mostly of river genesis. The Al content (indicator of terrigenous material) in SPM of the Kara Sea frequently exceeds 2%, which was higher as compared with that in other shelf seas (Baltic, White). Away from the areas influenced by the sediment river discharge, the share of terrigenous material gradually decreased. In 2007, the influence of terrigenous material in this direction became insignificantly weaker and its unusually high share was observable up to the southern periphery of the St. Anna Trough.

The SPM of the Kara Sea (similar to that in the White Sea, which was also highly influenced by mineral material transported by rivers) was characterized by transitional (from riverine to marine type) or mixed type of composition. The true "marine" type (organic or siliceous, according to [40]) of the SPM in the Kara Sea was usually observable beyond the shelf.

The significant annual variations in the SPM concentrations both in the surface and bottom waters were found in the western branch of the St. Anna Trough due to hydrological activity in this area. The powerful bottom nepheloid layer (~4 mg/L, water depth 550 m) formed occasionally in this area.

The nepheloid layer was observed practically everywhere within the Kara Sea shelf. Its thickness ranging from a few to several tens of meters and the SPM concentration varying from several to tens mg/L were controlled by water depth, wind velocity, currents, grain-size composition of bottom sediments, tide phases, and other factors.

ACKNOWLEDGMENTS

We are grateful to M.V. Flint, the head of the expeditions for his support of this work, Academician A.P. Lisitzin for scientific supervision and criticism, I.A. Nemirovskaya for her attention to these researches, O.V. Kopelevich, V.V. Kremenetskiy, S.A. Shchuka, N.A. Belyaev, M.S. Ponyaev, Yu.A. Gol'din, A.V. Grigor'ev, E.O. Zolotykh, L.V. Demina, and V.A. Karlov for their help in sampling and treatment of material. This work was supported by the Presidium of the Russian Academy of Sciences (program no. 44P "Pioneering basic scientific researches in connection with development of the Arctic zone of the Russian Federation," Russian Foundation for Basic Research (project nos. 12-05-00210-a, 12-05-91055-NTsNI_a, 14-05-00223-a), and Foundation of the President of the Russian Federation (grant no. NSh-2493.2014.5) and the Russian Science Foundation (grant no. 14-50-00095).

REFERENCES

1. N. A. Belyaev, V. I. Peresypkin, and M. S. Ponyaev, "The organic carbon in the water, the particulate matter, and the upper layer of the bottom sediments of the west Kara Sea," Oceanology (Engl. Transl.) **50** (5), 706–715 (2010).
2. V. I. Burenkov, Y. A. Goldin, V. A. Artem'ev, and S. V. Sheberstov, "Optical characteristics of the Kara Sea derived from ship borne and satellite data," Oceanology (Engl. Transl.) **50** (5), 716–729 (2010).
3. V. I. Burenkov, Y. A. Goldin, and M. D. Kravchishina, "The distribution of the suspended matter concentration in the Kara Sea in September 2007 based on ship and satellite data," Oceanology (Engl. Transl.) **50** (5), 798–805 (2010).
4. V. I. Vedernikov, A. B. Demidov, and A. I. Sud'bin, "Primary production and chlorophyll in the Kara Sea in September 1993," Oceanology (Engl. Transl.) **34** (5), 693–703 (1994).
5. R. E. Vlasenkov and A. P. Makshtas, "Hydrooptical characteristics of the Kara and Laptev seas," in *Oceanography and Marine Ice* (Paulsen, Moscow, 2011), pp. 208–225.
6. R. E. Vlasenkov and A. P. Makshtas, "Study of spatiotemporal characteristics of distribution of suspended matter in surface layer of the shelf seas of Russian Arctic," Probl. Arkt. Antarkt. No. 2, 63–71 (2012).
7. E. M. Galimov, *Nature of Biological Fractioning of Isotopes* (Nauka, Moscow, 1981) [in Russian].
8. E. M. Galimov, L. A. Kodina, O. V. Stepanets, and G. S. Korobeinik, "Biogeochemistry of the Russian Arctic. The Kara Sea: research results under the SIRRO project, 1995–2003," Geochem. Int. (Engl. Transl.), **44** (11), 1053–1104 (2006).
9. E. M. Gel'man and I. Z. Starobina, *Photometric Methods of Determination of Mineral-Forming Elements in Ores, Rocks, and Minerals* (Institute of Geochemistry and Analytical Chemistry, Acad. Sci. SSSR, 1976) [in Russian].
10. V. V. Gordeev, "Rivers of Russian Arctic: flows of sediments form continent to an ocean," in *New Concepts in Oceanology*, M. E. Vinogradova and S. S. Lappo (Nauka, Moscow, 2004), Vol. 2, pp. 113–166.
11. V. V. Gordeev, *River Inflow to the Ocean and Its Geochemistry* (Nauka, Moscow, 1983).
12. E. M. Emelyanov, *Barrier Zones in an Ocean: Sedimentation and Mineralization, Geoecology* (Yantarnyi Skaz, Kaliningrad, 1998) [in Russian].
13. P. O. Zavialov, "A report of the complex studies of the upper layer," in *A Report on Results of the Cruise 59th of R/V Akademik Mstislav Keldysh* (Institute of Oceanology, Russian Academy of Sciences, Moscow, 2012), pp. 72–88.
14. A. G. Zatsepin, P. O. Zavialov, V. V. Kremenetskiy, S. G. Poyarkov, and D. M. Soloviev, "The upper desalinated layer in the Kara Sea," Oceanology (Engl. Transl.) **50** (5), 657–667 (2010).
15. A. G. Zatsepin, E. G. Morozov, V. T. Paka, A. N. Demidov, V. V. Kremenetskiy, S. G. Poyarkov, A. A. Kondrashov, A. O. Korzh, and D. M. Soloviev, "Circulation in the southwestern part of the Kara Sea in September 2007," Oceanology (Engl. Transl.) **50** (5), 643–656 (2010).
16. G. I. Ivanov, V. P. Shevchenko, and A. V. Neshcheretov, "Cruise to the St. Anna Trough," Priroda, No. 10, 56–62 (1995).
17. M. V. Ivanov, A. S. Savvichev, and A. Y. Lein, "Effect of phytoplankton and microorganisms on the isotopic composition of organic carbon in the Russian Arctic seas," Microbiology (Engl. Transl.) **79** (5), 567–582 (2010).
18. L. A. Kodina, M. P. Bogacheva, L. N. Vlasova, and E. M. Galimov, "Particulate organic matter from the Yenisei estuary: isotopic composition, distribution, and genesis," Geochem. Int. (Engl. Transl.) **37** (11), 1087–1096 (1999).
19. N. V. Koronovskii, *Brief Lecturers on Regional Geology of the Soviet Union* (Moscow State University, Moscow, 1984) [in Russian].

20. M. D. Kravchishina and A. P. Lisitzin, "Grain-size composition of the suspended particulate matter in the marginal filter of the Severnaya Dvina River," Oceanology (Engl. Transl.) **51** (1), 89–104 (2011).

21. M. D. Kravchishina, I. N. Mitzkevich, E. F. Veslopolova, V. P. Shevchenko, and A. P. Lisitzin, "Relationship between the suspended particulate matter and microorganisms in the White Sea waters," Oceanology (Engl. Transl.) **48** (6), 837–854 (2008).

22. M. D. Kravchishina, V. P. Shevchenko, A. S. Filippov, A. N. Novigatskii, O. M. Dara, T. N. Alekseeva, and V. A. Bobrov, "Composition of the suspended particulate matter at the Severnaya Dvina River mouth (White Sea) during the spring flood period," Oceanology (Engl. Transl.) **50** (3), 365–385 (2010).

23. V. V. Kremenetskiy, "A report of hydrophysical group," in *A Report on Results of the Cruise 59th of R/V Akademik Mstislav Keldysh* (Institute of Oceanography, Russian Academy of Sciences, Moscow, 2012), pp. 1–70.

24. A. A. Krylov, G. I. Ivanov, and E. I. Sergeeva, "Recent sedimentation in the St. Anna Trough (Kara Sea)," Oceanology (Engl. Transl.) **45** (1), 99–107 (2005).

25. E. V. Lazareva, A. M. Parfenova, and N. D. Romanova, "Influence of nanoplankton on integrity of natural colloid systems at different salinity levels," in *Proceedings of the XX International Conference on Marine Geology "Geology of the Seas and Oceans"* (GEOS, Moscow, 2013), Vol. 4, pp. 85–87.

26. M. A. Levitan, M. V. Burtman, Z. N. Gorbunova, and E. G. Gurvich, "Quartz and feldspars in upper layer of bottom sediments of the Kara Sea," Litol. Polezn. Iskop., No. 2, 115–125 (1998).

27. A. Y. Lein, P. N. Makkaveev, A. S. Savvichev, M. D. Kravchishina, N. A. Belyaev, O. M. Dara, M. S. Ponyaev, A. G. Rozanov, M. V. Flint, E. E. Zakharova, and M. V. Ivanov, "Transformation of suspended particulate matter into sediment in the Kara Sea in September of 2011," Oceanology (Engl. Transl.) **53** (5), 570–606 (2013).

28. A. Yu. Lein, I. I. Rusanov, A. S. Savvichev, N. V. Pimenov, Yu. M. Miller, M. V. Ivanov, and G. A. Pavlova, "Biogeochemical processes of the sulfur and carbon cycles in the Kara Sea," Geochem. Int. (Engl. Transl.) **34** (11), 925–941 (1996).

29. A. P. Lisitzin, "Sediment fluxes, natural filtering, and sedimentary systems of a "living ocean"," Russian Geology and Geophis. **45** (1), 15–48 (2004).

30. A. P. Lisitzin and M. E. Vinogradov, "International high-latitude expedition in the Kara Sea (cruise 49 of R/V *Dmitrii Mendeleev*)," Okeanologiya (Moscow) **34** (5), 643–652 (1994).

31. A. P. Lisitzin, M. D. Kravchishina, O. V. Kopelevich, V. I. Burenkov, V. P. Shevchenko, S. V. Vazyulya, A. A. Klyuvitkin, A. N. Novigatskii, N. V. Politova, A. S. Filippov, and S. V. Sheberstov, "Spatial and temporal variability in suspended particulate matter concentration within the active layer of the White Sea," Dokl. Earth Sci. **453** (2), 1228–1233 (2013).

32. A. P. Lisitzin, V. N. Lukashin, E. M. Emelyanov, and I. B. Zverinskaya, "Aluminium," in *Geochemistry of the Elements-Hydrolysates*, Ed. by A. B. Ronov (Nauka, Moscow, 1980), pp. 18–49.

33. A. P. Lisitsyn, V. P. Shevchenko, and V. I. Burenkov, "Hydrooprics and suspended matter of Arctic seas," Atmos. Ocean. Opt. **13** (1), 61 (2000).

34. V. N. Lukashin, S. V. Lyutsarev, V. P. Shevchenko, V. Yu. Rusakov, and A. D. Krasnyuk, "Suspended matter in estuaries of the Ob' and Yenisei rivers: data from the 28th cruise of R/V *Akademik Boris Petrov*," Geochem. Int. **38** (12), 1221–1236 (2000).

35. V. N. Lukashin, V. L. Stryuk, and E. G. Gurvich, "Forms of iron, magnesium, cooper, zinc, aluminium, and titanium in the mixing zone of waters of the Kurshskii Bay and Baltic Sea," Geokhimiya, No. 4, 545–556 (1987).

36. P. R. Makarevich and V. V. Larionov, "Annual cycle of the planktonic phytocenosis in the Ob-Yenisei shallow zone of the Kara Sea," Russ. J. Mar. Biol. (Engl. Transl.) **37** (1), 1–6 (2011).

37. P. N. Makkaveev, P. A. Stunzhas, Z. G. Mel'nikova, P. V. Khlebopashev, and S. K. Yakubov, "Hydrochemical characteristics of the waters in the western part of the Kara Sea," Oceanology (Engl. Transl.) **50** (5), 688–697 (2010).

38. N. G. Platonov, I. N. Mordvintsev, V. V. Rozhnov, and I. V. Alpatskii, "Analysis of glacial cover of Arctic during summer minimum of 2011," Issled. Zemli Kosmosa, No. 4, 12–25 (2012).

39. N. V. Politova, Candidate's Dissertation in Geology-Mineralogy (Moscow, 2007).

40. O. S. Pustelnikov, "Organic matter in suspends and its sedimentation on the bottom of Baltic Sea," Okeanologiya (Moscow) **15** (6), 1040–1045 (1975).

41. F. A. Romanenko, "Intensity of geomorphologic processes on the islands and coasts of the Kara and Laptev seas (according to the observations of Polar stations)," Geomorfologiya, No. 1, 56–64 (2008).

42. A. B. Ronov and A. A. Yaroshevskii, "Chemical structure of the Earth's crust," Geokhimiya, No. 11, 1285–1309 (1967).

43. A. S. Savvichev, E. E. Zakharova, E. F. Veslopolova, I. I. Rusanov, M. V. Ivanov, and A. Y. Lein, "Microbial processes of the carbon and sulfur cycles in the Kara Sea," Oceanology (Engl. Transl.) **50** (6), 893–908 (2010).

44. *System of the Laptev Sea and the Adjacent Arctic Seas: Modern and Past Environments*, Ed. by H. Kassens et al. (Moscow State University, Moscow, 2009) [in Russian].

45. V. M. Smolyanitskii, T. V. Sheveleva, A. B. Timofeeva, and A. V. Yulin, "Development and status of glacial cover in the Arctic Ocean during International Polar Sea according to the data of continuous monitoring," in *Oceanography and Marine Ice* (Paulsen, Moscow, 2011), pp. 319–328.

46. I. N. Sukhanova, M. V. Flint, S. A. Mosharov, and V. M. Sergeeva, "Structure of the phytoplankton communities and primary production in the Ob River estuary and over the adjacent Kara Sea shelf," Oceanology (Engl. Transl.) **50** (5), 743–758 (2010).

47. I. N. Sukhanova, M. V. Flint, V. M. Sergeeva, and V. V. Kremenetskiy, "Phytoplankton of the south-western part of the Kara Sea," Oceanology (Engl. Transl.) **51** (6), 978–992 (2011).

48. L. A. Timokhov, I. M. Ashik, V. Yu. Karpii, et al., "Extreme changes of water temperature and salinity of the Arctic surface layer in 2007–2009," in *Oceanography and Marine Ice* (Paulsen, Moscow, 2011), pp. 118–137.

49. M. V. Flint, "Cruise 54th of the research vessel *Akademik Mstislav Keldysh* in the Kara Sea," Oceanology (Engl. Transl.) **50** (5), 637–642 (2010).

50. A. N. Charkin, Candidate's Dissertation in Geology-Mineralogy (Vladivostok, 2012).

51. V. P. Shevchenko, O. V. Severina, N. G. Maiorova, and G. V. Ivanov, "Quantitative distribution and composition of suspended matter in the Ob' and Yenisei estuaries," Vestn. Mosk. Univ., Ser. 4: Geol., No. 3, 81–86 (1996).

52. J. D. Benson, M. A. Haidekker, C. M. K. Benson, and J. K. Critser, "Mercury free operation of the Coulter Counter Multisizer II sampling stand," Cryobiology **51** (3), 344–347 (2005).

53. E. R. M. Druffel and P. M. Williams, "Importance of isotope measurements in marine organic chemistry," Mar. Chem. **39** (1–3), 29–215 (1992).

54. A. C. Gebhardt, "Modern sedimentation processes in the Kara Sea (Siberia)," Ber. Polarforsch. Meeresforsch. **490**, (2004).

55. W. Jambers, A. Smekens, R. van Grieken, et al., "Characterization of particulate matter from the Kara Sea using electron probe X-ray micro analysis," Colloids Surf., A **120**, 61–75 (1997).

56. L. A. Kodina, "Carbon isotope composition of phytoplankton in the Yenisei River estuary—open sea system and the application of isotopic approach for evaluation of phytoplankton contribution to the Yenisei POC load," Rep. Polar Mar. Res. **419**, 143–150 (2002).

57. O. V. Kopelevich, V. I. Burenkov, and S. V. Sheberstov, "Case studies of optical remote sensing in the Barents Sea, Black Sea, and Caspian Sea," in *Remote Sensing of the European Seas*, Ed. by V. Barale and M. Gade (Springer-Verlag, Berlin, 2008), pp. 53–66.

58. M. Kravchishina, A. Lein, V. Burenkov, et al., "Distribution and sources of suspended particulate matter in the Kara Sea," in *Proceedings of IAHS-IAPSO-IASPEI Assembly "Complex Interfaces under Change: Sea–River–Groundwater–Lake* (IAHS, Oxford, 2014), Vol. 365, pp. 1–7.

59. O. A. Kuznetsova, O. V. Kopelevich, V. I. Burenkov, et al., "Development of the regional algorithm for assessment of suspended matter concentration in the Kara Sea from satellite ocean color data," in *Proceedings if the VII International Conference "Current Problems in Optics of Natural Waters, ONW'2013* (Nauka, St. Petersburg, 2013), pp. 177–181.

60. P. C. Lightfoot, A. J. Naldert, N. S. Gorbachev, et al., "Geochemistry of the Siberian Trap of the Norilsk area, USSR, with implication for the relative contributions of crust and mantle to flood basalt magmatism," Contrib. Mineral. Petrol. **104**, 631–644 (1990).

61. J. Matiessen, M. Kunz-Pirrung, and P. J. Mudie, "Freshwater chlorophycean algae in recent marine sediments of the Beaufort, Laptev and Kara seas (Arctic Ocean) as indicators of river runoff," Int. J. Earth Sci. **89**, 470–485 (2000).

62. B. Nagel, B. Gaye, L. A. Kodina, and N. Lahajnar, "Stable carbon and nitrogen isotopes as indicators for organic matter sources in the Kara Sea," Mar. Geol. **266**, 42–51 (2009).

63. N. V. Politova, V. P. Shevchenko, and V. V. Zernova, "Distribution, composition, and vertical fluxes of particulate matter in bays of Novaya Zemlya Archipelago, Vaigach Island at the end of summer," Adv. Meteorol., 1–15 (2012). Article ID 259316

64. F. Schoster and R. Stein, "Major and minor elements in surface sediments of Ob and Yenisei estuaries and the adjacent Kara Sea," Ber. Polarforsch., No. 300, 196–207 (1999).

65. V. P. Shevchenko, A. P. Lisitzin, G. I. Ivanov, et al., "Quantitative distribution of suspension and suspended organic carbon in the Kara and Barents Seas," in *Natural Conditions of the Kara and Barents Seas*, Ed. by V. Volkov et al. (Norsk Polarinstitut, Oslo, 1997), pp. 431–435.

66. R. Stein, "Circum Arctic river discharge and its geological record," Int. J. Earth Sci. **89**, 447–449 (2000).

67. R. Stein and K. Fahl, "The Kara Sea: distribution, sources, variability and burial of organic carbon," in *The Organic Carbon Cycle in the Arctic Ocean*, Ed. by R. Stein and R. W. Macdonald (Springer-Verlag, Berlin, 2004), pp. 237–266.

68. A. Vasiliev, M. Kanevsky, G. Cherkashov, and B. Vanshtein, "Permafrost and coastal dynamics at the Barents and Kara Sea key sites," Geo-Mar. Lett. **25** (22–23), 110–120 (2005).

Translated by I. Basov