Suspended Particulate Matter as a Main Source and Proxy of the Sedimentation Processes

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Contents

Abstract The material for our study was collected in the White Sea during 22 interdisciplinary expeditions organized by the Shirshov Institute of Oceanology, Russian Academy of Sciences (IO RAS), in 2000–2014. The researches were carried out mostly in June–August; however we have some samples for autumn–winter and early spring seasons. Here, we report the concentration of suspended particulate matter (SPM), its composition and properties, as well as their changes due to natural zoning and local conditions. This paper discusses the features in the distribution of

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SPM concentration, grain-size, mineral, and major phase composition. As far as possible, we involved our own and other published data on hydrology, bottom morphology, and particulate and dissolved river runoff from the catchment area, abundance and composition of marine phyto- and bacterioplankton. This new knowledge has been used to describe particles dispersion system of the White Sea, which forms a giant reservoir of micro- and nanoparticles, using terms adopted in sedimentology and oceanography.

1 Introduction

The collection of samples and study of suspended particulate matter (SPM) for understanding some basic problems in sedimentology was first carried out by Lisitsyn in the Bering Sea in 1951 [1]. Studies of SPM in the White Sea, Russia, were initiated by Medvedev and Krivonosova in 1966, using a method developed by Lisitsyn [2]. Important quantitative characteristics were obtained for the distribution of SPM mass concentrations (in mg/L) and supplying of terrigenous particles. Subsequently, these studies were conducted by Aibulatov [3] and then by Lukashin and Dolotov [4–6] in the White Sea.

The study of SPM as a dispersed system requires an integrated approach, namely, combining the biological, hydrological, optical, geochemical, and geological parameters of marine environment. Integrated researches in the White Sea started in 2000 in the frame of the project "The White Sea System" [7].

Water sampling for the SPM study was preceded by a profiling instrument package measuring hydrooptical (beam attenuation coefficient, light scattering – proxies for particle concentration), hydrophysical (conductivity, temperature, depth), and biogeochemistry (fluorometer – proxy for phytoplankton, oxygen, pH, Eh) parameters of the water column and was accompanied by sampling for nutrients; bacterio-, phyto-, and zooplankton; and other special biogeochemical researches (methane concentration, rates of biogeochemical processes, etc.). Satellite ocean color data were used to show the areal distribution of SPM, chlorophyll, temperature, and other bio-optical parameters in the surface layer of the White Sea on many time scales [8–10].

The study of marine SPM provides knowledge on the cause-effect relationships of the recent sedimentation process (from the source of matter to bottom sediments deposition) and is a reliable basis for quantitative assessments of this process. For geochemists and sedimentologists, the SPM is a matter of interest not only as a material for the formation of bottom sediments but also as one of the occurrence forms of chemical elements and phases in seawater [11–13]. The marine SPM is one of the most powerful adsorbents on the Earth.

The SPM is a heterogeneous material and normally includes abiotic (mineral) and biotic (phytoplankton, detritus, partially bacterioplankton, spores) particles. The SPM participates in biogeochemical processes as a primary reacting substance or catalyst, and it is utilized by zooplankton and benthos during feeding via biofiltration. Marine particles participate in phase-to-phase transitions; their surface charge can change followed by alteration of their aggregative stability or coagulation and flocculation. SPM can exhibit the properties of some colloids and at the same time obeys the Stokes law [14].

There are many other reasons to be interested in SPM concentration and composition. Particles in the sea have a different grain-size and density; they scatter light and sound differently, have different specific surface areas, and, consequently, have different physicochemical ability and sedimentation rates. Bacteria, as well as SPM, are a dispersed phase, and they can affect the optical and other properties of seawater [15].

One of the main components of SPM in seas is a particulate organic matter (POM): terrigenous (allochthonous "humic") and biogenic (autochthonous "sapropelic"). Chlorophyll "a" (Chl-a) is the most important component of the primary organic matter, is present in almost all microalgae, and acts as a marker of phytoplanktonic material in SPM. Chl-a and its derivatives can be regarded as a proxy of the labile form of organic carbon [16]. In water column and bottom sediments, they characterize the contribution of only phytoplankton, and no other sources of organic matter.

In the Russian Arctic and Subarctic seas, to which the White Sea belongs, the SPM concentration and composition are still poorly understood. The new data will allow us to expand our knowledge of the recent sedimentation in the Arctic shelf seas, which are under the influence of climate change [17]. This is an important issue for the planned expansion of operations and investigations in the Arctic.

The Arctic seas, such as the White Sea, are subjected to a powerful river runoff and coastal abrasion, so terrigenous (allochthonous) material is an important and often predominant fraction of the total SPM [18–20]. The biogenic (autochthonous) component of the SPM usually has a secondary significance, the share of which depends on the primary production. Production and destruction of organic matter, river runoff, supply of biogenic elements, and many other processes in the White Sea have pronounced seasonal features [18, 21, 22].

The aim of this chapter is to present the results of long-term (2000–2012) interdisciplinary researches of the SPM (concentration and major phase composition) in the White Sea for understanding of the recent processes operating in the shelf seas and their role in the Arctic Ocean. Here, we report the SPM data in euphotic zone and on full-depth sections. This paper discusses the main features in the distribution of SPM concentration and bacterioplankton abundance, grain-size, major constituents content (POC, particulate inorganic carbon (PIC), Chl-a, lithogenic particles, etc.), and mineral composition. It allowed us to reveal the sources of the SPM and the features of the spatial and temporal variability of its concentration and composition in the White Sea.

2 Materials and Methods

The materials for our study were collected in the 22 interdisciplinary expeditions organized by IO RAS (28 expeditions, including works in the river–sea interface) (Fig. 1). Our research is based on SPM samples collected in the White Sea over 2000–2014.

Full sea depth sampling occurred on the basis of the hydrooptical (transmissometers, IO RAS) and hydrophysical (CTD Idronaut Ocean 316, Sea&Sun 90M, and SBE 25 plus) sounding profiles. The effect of hydrological conditions on the formation of extremes of suspended matter concentration was estimated. The paper [23, 24] reports on the hydrology and currents in the White Sea. Chemical composition of particulate and dissolved river runoff is presented in the paper [25], phytoplankton researches in [26], and biogeochemical processes in [22]. Water samples were taken using Niskin bottles and Rosette devices.

The SPM mass concentration was determined by the standard technique of vacuum filtration at 400 mbar using membrane filters (diameter 47 mm, pore diameter 0.45 μm) [1, 27, 28]. Each sample (~5 L) was simultaneously filtered through three or more membrane filters. The concentration was determined by
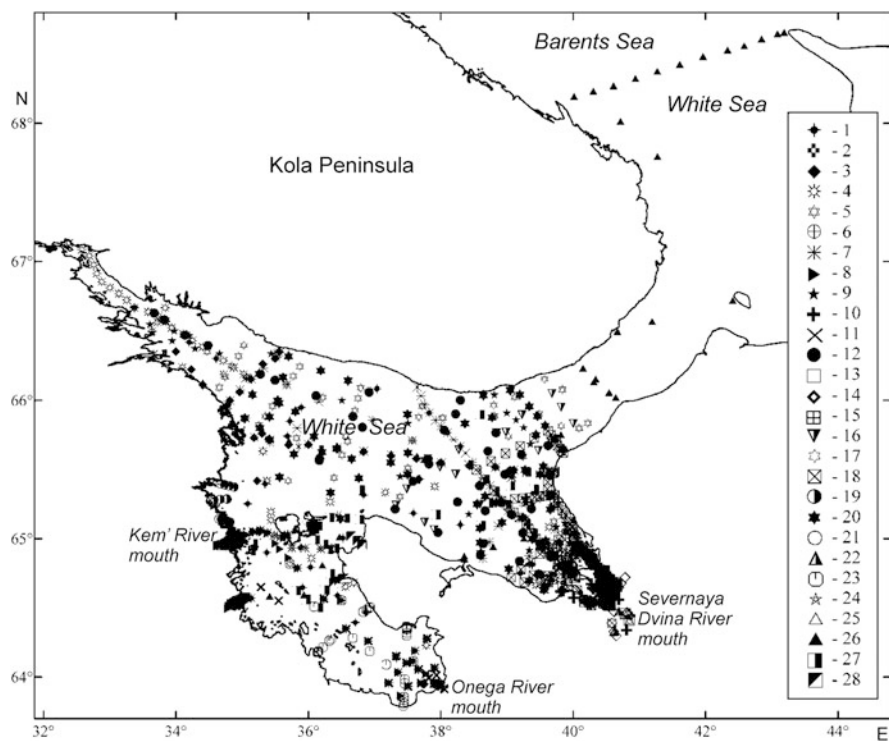
Fig. 1 The study sites of SPM in the White Sea during 28 expeditions of IO RAS, 2000–2014

weighing the filters within accuracy ±0.01 mg, correlating with the volume of filtered water. Total number of samples is 3,500.

The Multisizer™ 3 modification of a Coulter counter®, Beckman Coulter, USA (~2,000 samples), was used to determine the concentration by volume and grain-size (in the range of 2–60 μm) of the SPM [14, 29]. The device was calibrated on board the vessel using a standard latex suspension with a nominal particle size of 5 μm (Coulter® CC Size Standard L5).

SPM grain-size (1.22–118 μm) measurement in fresh river waters was carried out using a Malvern 3600Ec, UK, laser diffraction analyzer (15 samples).

For the total count of the microorganisms, water samples were filtered through Millipore ISOPORE black polycarbonate filters 25 mm in diameter with a pore size of 0.2 μm (246 samples). For more details see [30, 31].

The concentration of Chl-a and pheophytin "a" (Pheo-a) was determined in the samples with fluorometry (with extraction in 90% acetone) on a Trilogy 1.1 fluorometer, Turner Designs, USA, according to the approach described in [32]. The fluorometer was calibrated using the standard powder Chl-a, C6144–IMG Sigma, Austria. The share of Pheo-a (%) was calculated from the sum of Chl-a and Pheo-a.

Before determination of the Chl-a concentration, POC, PIC, and its isotopic composition ($\delta^{13}C_{POC}$), water samples were filtered under a vacuum of 200 mbar through Whatman GF/F glass fiber filters (diameter 47 mm, nominal pore size of 0.7 μm) precombusted at 450°C for 4 h.

The POC and bulk particulate carbon were determined by the automatic coulometric method on an AN 7560 carbon analyzer, Russia. Then, the PIC was determined as the difference between these two values. For a concentration of 30–100 μg C/L, the accuracy was ±15%, and the measurement range was 5–500 μg C/L. The POM content was determined as POC × 2 [33].

Values of $\delta^{13}C_{POC}$ were determined after conventional preparation of samples on a Delta Plus mass spectrometer, Germany, using the PDB standard with an accuracy of ±0.2‰ [18, 22, 31].

The Si, Al, and P content in the SPM were determined by the photometric method in line with the procedure [34] and modified for small weighed portions at the filter by Isaeva and Lukashin, IO RAS [35]. The accuracy of this method is ±15%. We use Al as a tracer of lithogenic particles. We use the upper continental crust Al content of 8.04% to calculate lithogenic phase of SPM [36].

The composition and morphology of the individual particles of the SPM were studied by use of the VEGA-3sem TESCAN scanning electron microscope, Czechia, equipped with the X-ray spectral microprobe Oxford INCA Energy 350, Great Britain.

X-ray powder diffractometry was used to study the mineral composition of the SPM: DRON-2.0 X-ray diffractometer, Russia, and Bruker D8 Advance system, Germany [37].

Data obtained with a MODIS-Aqua satellite ocean color scanner (http:// oceancolor.gsfc.nasa.gov/) were used to analyze the areal distribution of water temperature, Chl-a, and SPM, in the surface water layer. Images of the distribution

patterns of these parameters were compiled, using regional algorithms developed at the Laboratory of Ocean Optics, IO RAS, from our original field measurements [8, 10, 38].

For the White Sea, estimation of bio-optical parameters by the satellite data is not an easy procedure, since several factors deteriorate correct calculation, including the low Sun position above the horizon (this increases the number of errors in calculating the atmospheric corrections), high clouds, and intensive riverine discharge with high content of colored dissolved organic matter (CDOM) [10, 38]. Development of algorithms that may be applied in local and seasonal aspects in the shelf seas is essential for reliable assessment of the satellite data; and this can be done only when referring to the field data.

3   Characteristic of Sedimentation Area

Compared to the other Russian Arctic shelf seas, the White Sea is a distinctive basin because it is semi-enclosed. It has quite small dimensions (area about 90,000 km^2, a volume of 5,375 km^3, an average depth about 67 m, the maximum one of 350 m), has a strongly partitioned shape, and receives a fluvial input from a relatively large catchment area of 715,000 km^2 [17, 39]. River runoff makes a dominant contribution to the freshwater budget (a total annual discharge of about 225–231 km^3) and little influence of sea ice formation or melt [40]. There are major rivers Severnaya Dvina (112 km^3/year), Mezen (24 km^3/year), and Onega (18 km^3/year) in the eastern part of the sea and many small rivers in the western part (Fig. 2). The bulk of the terrigenous matter is supplied to the White Sea with riverine runoff during spring flood which exceeds its supply during the summer mean water in two or more times [41]. The SPM concentrations varied usually from 2.0 to 11.6 mg/L in the delta of the Severnaya Dvina River in summer [9]. Despite the fact that the turbidity of river waters is not so significant, the total amount of particulate river runoff may be quite appreciable due to abundant annual runoff.

River waters are enriched in different forms of DOM including humates of iron and manganese [47]. Mean concentration of dissolved organic carbon (DOC) in the Severnaya Dvina River is 18 ± 2 mg/L [42]. Values of absorption by CDOM at 350 nm and DOC in surface waters of the White Sea basin are higher compared to other river-influenced coastal Arctic domains [40]. In this regard, the waters of the White Sea are characterized by the strongest absorption of solar radiation in comparison with the Kara Sea (subjected to huge river runoff) and especially the Barents Sea (with a small river runoff). Almost all the solar radiation entering the water is absorbed already in the upper 10–15-m layer [43].

The White Sea is characterized by a short vegetation period (210–123 days/year in different parts of the sea) [39]. Significant temporal and spatial variability in
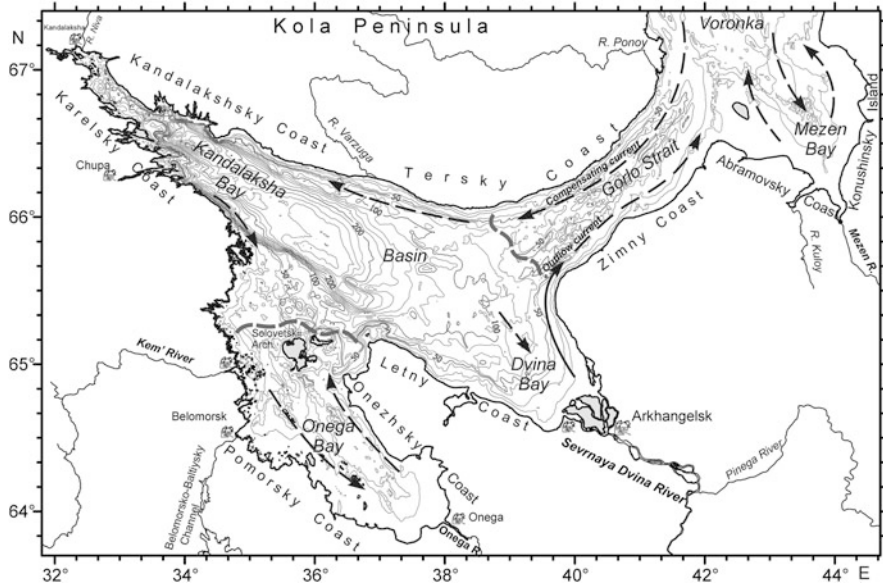
Fig. 2 The map of the White Sea, its bathymetry (based on IO RAS and GEBCO bathymetry), major currents shown by black arrows, and hydrological fronts shown by gray-dashed line (data from [23, 24])

euphotic zone primary productivity obviously causes variations in particle concentrations in the upper water layer [26].

The surface salinities are 24–28 and about 30 psu near the bottom [23]. Interaction between water masses of the White and Barents Seas is controlled by strong tidal mixing in the narrow and the relatively shallow Gorlo Strait, where current velocities of up to 2.5 m/s have been reported [17]. Tides flow into the White Sea from the Barents Sea as regular semidiurnal waves [14]. A water residence time is 5–6 years which is longer than that in neighboring Arctic shelf seas (1–2 years for the Kara Sea). Water masses from the Barents Sea have the Atlantic origin. They are characterized by a consistently high salinity of 34–35 psu and a relatively high temperature for the Arctic seas varying by seasons within about 3–8°C [23] (Fig. 3).

Waters with a quasi-homogeneous vertical distribution pattern of thermohaline characteristics are confined to the Gorlo and Onega Bay (due to tidal mixing) and stratified waters – to the Basin, Dvina, and Kandalaksha Bays. Nearby the large river inlets (such as the Severnaya Dvina, Onega, and Mezen) as well as between Gorlo and Basin, and between Onega Bay and Basin, the distinct hydrographic fronts are commonly found [24, 44].

It was revealed the climate warming in the Arctic Region has caused a reduction in freshwater inflow into the White Sea and an increase in evaporation [17] that may influence the SPM sources into the sea.
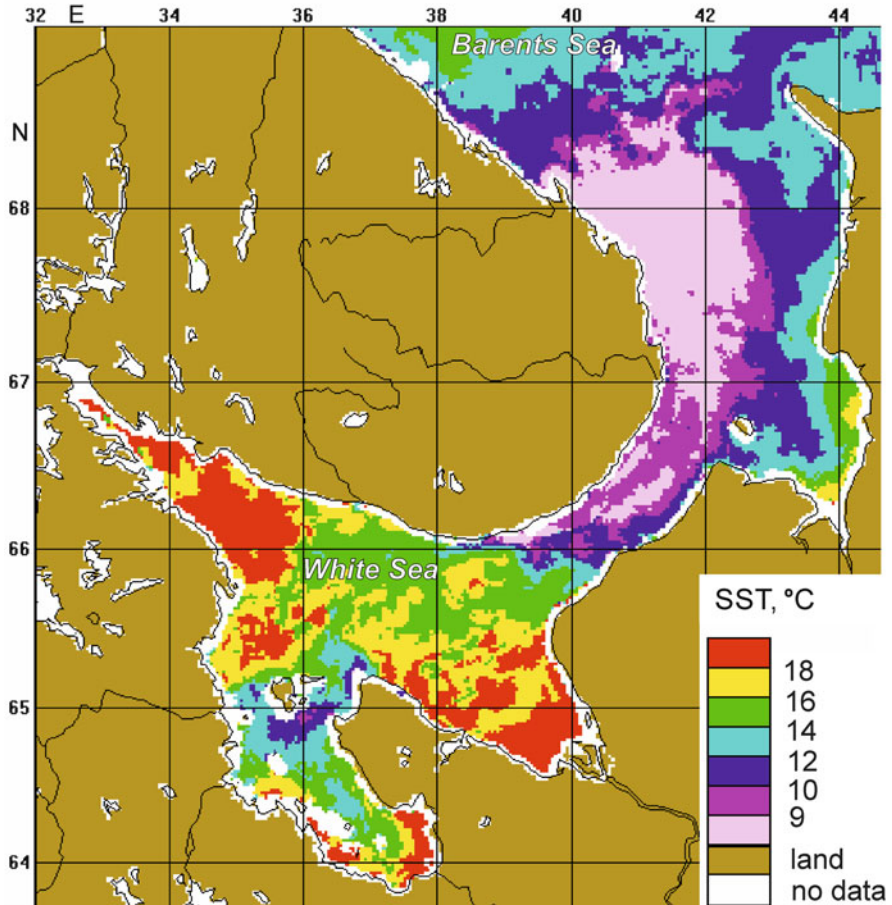
Fig. 3 Sea surface temperature (SST) distribution in the White Sea derived from MODIS-Aqua data. Image was composited over August 1–28, 2003, and provided by IO RAS, Ocean Optic Laboratory

4 SPM Sources

The distribution and dynamics (seasonal and interannual variations in the amount and composition) of SPM are determined by the sources of SPM. The main sources are allochtonous material (mostly transported by large rivers) and autochtonous (biogenic) matter. Allochtonous matter is supplied primarily by the Severnaya Dvina River (the peak is during flood in May). The distribution pattern of autochtonous material is determined by primary production.

In the beginning of the hydrological spring, the main SPM sources are cryosols and algal flora which are supplied during the sea- and river-ice melting. Mean concentration of particulate matter in sea-ice is about 5 mg/L [20]. This is a substantially lower

value than that for Siberian shelf seas. The sediment laden sea-ice is composed of mostly biogenic matter (diatoms, as a rule) [45]. The beginning of the biological spring is observed in the first decade of April.

Phytoplankton abundant in the White Sea is characterized by two maxima: in April–May and in June–July with domination of diatoms. In the end of summer (sometimes in July) in addition to diatoms, dinoflagellates dominated too [46]. Autumn phytoplankton blooms are usually weakly expressed.

Coastal abrasion material makes a significant contribution to the SPM concentration in the Mezen Bay and Voronka, on their eastern coasts [2]. The main part of material (first of all, the sandy–silty fraction) accumulates in the shallow tidal zone and in the zone of alongshore currents. In shallow Onega and Mezen Bays, resuspension processes caused by tidal currents and storm effects, at small depths, play a significant role.

Aerosols are one of the SPM sources. The concentration of insoluble aerosol particles above the sea is about 0.17 μg/m^3. This value is close to the average concentration for the Russian Arctic seas. The flux of aerosols to the water surface of the White Sea amounts 54,000 tons/year.

Evaluation of aerosol and coastal abrasion matter's fluxes is much lower than particulate river runoff. The total particulate runoff of three largest rivers (Northern Dvina, Mezen, and Onega rivers) is 5 million tons per year [19, 47]. If we take into account that about 70–80% (for different rivers) of the river particulate matter is deposited in the area of marginal filters [28], then approximately 250,000 tons/year of this material enters to the sea, which is about five times higher than the contribution of aerosols. Nevertheless, the supply of aerosols to the White Sea areas far from the large river mouths may be significant for some trace elements [48].

5 SPM Concentration by Mass and Volume in Surface Water Layer

The spatial and temporal variations in SPM concentration in the White Sea are caused by direct input of mineral particles from the catchment areas and river runoff, first of all the Severnaya Dvina River. Besides, there is an indirect SPM input resulted from diatom blooms which are controlled by supply of nutrients and quite narrow euphotic layer because of CDOM high content.

5.1 Mass Concentration of the SPM in Surface Layer

The typical SPM distribution pattern in the White Sea is presented in Fig. 4. Isoline positions can change significantly in the coastal zones, in areas of river marginal filters, and in frontal areas.
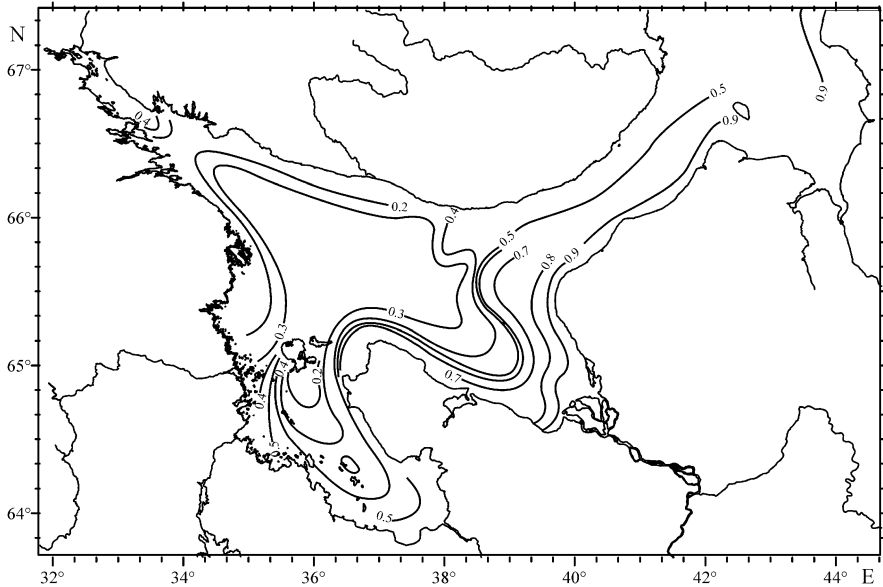
Fig. 4 The principle schematic map of the SPM distribution in the White Sea in summer, mg/L. Values of SPM concentrations are marked on isolines

The average SPM mass concentration beyond the river mouths was detected to be ~1.0–1.4 mg/L in the White Sea (June–September, 2000–2014). This value appeared to be close to the corresponding value in the Kara Sea (~1.2–1.3 mg/L on average for 2007 and 2011) and Laptev Sea (~1.7 mg/L on average for 2003, 2004, 2007, and 2008) [49]. Such a similarity is explained by the fact that these Arctic seas are subjected to strong influence of the river runoff, which controls the formation and spatial distribution of marine SPM. On the contrary, these values exceed the same parameter by 3–4 times in the Barents Sea where concentration usually varied from 0.2 to 0.5 mg/L, rarely to 1 mg/L, in summer 2017 [unpublished data] and autumn 1997-1998 [50].

Higher values of SPM concentration (>1 mg/L) were usually detected in the river mouth's area and located in a narrow (up to 20 km wide) coastal zone. Here, the complex structure of lateral fluxes of SPM is formed. This pattern is also evident in the other Arctic shelf seas [3, 49, 50]. Isolines of the higher SPM concentration generally run in parallel to the coastline (Fig. 3). The values of the SPM concentration decrease by a factor of 5–10 with distance off the coast. This phenomenon is characteristic for many shelf seas and coastal areas of the World Ocean [1].

SPM concentration may be changeable due to wind stress and tide phase. After the storm of July 2010 (intensity was up to 4 on the Beaufort scale), the water turbidity in the surface layer increased in 1.5–2 times (Fig. 5). Using the ADCP, the SPM dynamics dependence on the tidal cycle was studied at the diurnal stations: (a) the SPM concentration decrease in the high tide period, while it increases at low tide; and (b) variations in the SPM concentration within the whole water column
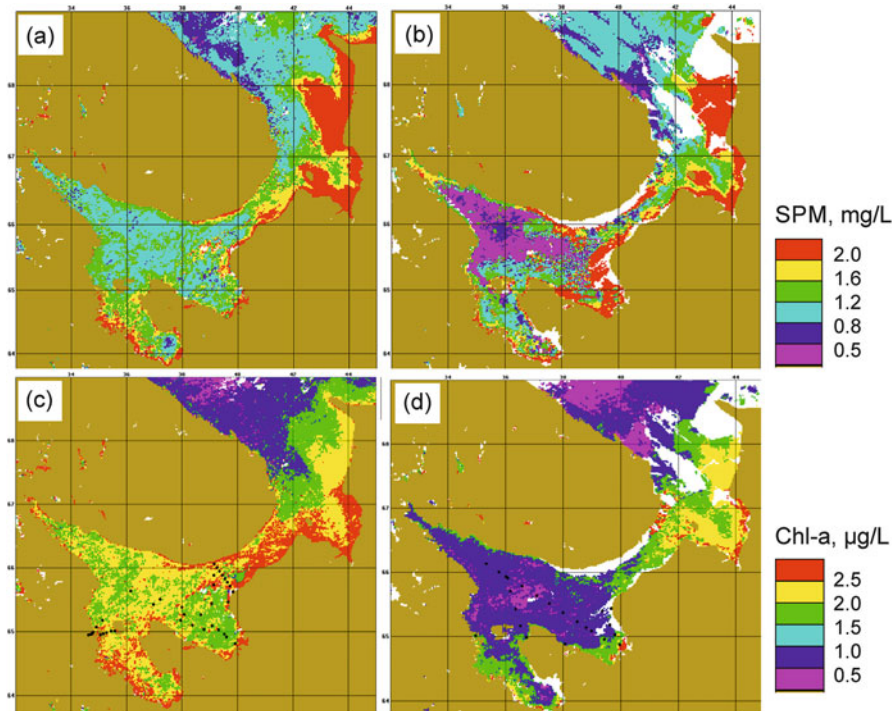
Fig. 5 The SPM and Chl-a concentration in the surface water layer of the White Sea before and after storm in July 2010. The SPM concentration (**a**) before storm, images were composited over July 20–24, (**b**) after storm, images were composited over July 25–29; Chl-a concentration (**c**) before storm and (**d**) after storm

reached 1.5-fold or even more (depending on the sea depth), both in the coastal and in distant zones (arbitrarily, down to the isobaths of 100 m) [10].

Despite the fact that the freshwater input of the Severnaya Dvina River is significantly higher than that of the Onega and Mezen Rrivers, the water turbidity is much larger in adjacent to the mouth areas of the latter. It's connected with powerful tidal mixing and resuspension processes in the Onega and Mezen Bays according to Dvina Bay.

In the central part of the White Sea (so-called Basin), SPM concentration varied from 0.3 to 0.8 mg/L, up to 1 mg/L locally. The likely reason for this is the anticyclonic water circulation in the White Sea, which transports the SPM along the coasts and prevents its inflow to the open sea areas. Excess water of low density (transformed water river) enters the Voronka and Barents Sea through the Gorlo Strait from the sea itself, where a constant outflow current (with SPM concentration about 1–2 mg/L) is directed along the eastern coast of the Dvina Bay and Gorlo Strait (Zimny Coast) (Fig. 2).

The Barents Sea waters enter the Basin through the Gorlo Strait mainly along the western Tersky Coast, compensating current (Fig. 3). The SPM concentration in these waters is noticeably lower (about 0.4 mg/L) than that along the eastern coast in

the outflow current. SPM concentration varied from 0.2 till 1 mg/L in the Voronka region. The trace of the White Sea own water was revealed near the northern boundary of the sea close to eastern coast [3].

Besides the anticyclonic circulation, hydrological fronts (tidal mixing fronts, local upwelling, currents, river marginal filters, etc.) distort the pattern of gradual decreasing of the SPM concentration in the off-the-coast direction. In these areas, gradient zones are formed (SPM fronts and biogeochemical barriers), and their positions can change seasonally.

The water salinity is the main factor that controls the changes in the SPM distribution in the marginal filter of the rivers [28, 51]. The SPM concentration decreases exponentially by up to 79% as salinity grows in the marginal filter area of the Severnaya Dvina River. So, close to the mouth area, concentration reached 6–3 mg/L in June and August, respectively.

A quasi-constant zone of low-temperature anomaly, located southeast of the Solovetsky Archipelago, is characterized by low SPM concentration (up to 0.2 mg/L) (Fig. 3). Primary production here is minimal due to wind stress at small depths that, however, promotes increase in the photic layer thickness [52].

In the Basin and Kandalaksha Bay, increased SPM concentration (>1 mg/L) was usually related to local phytoplankton growth, under the condition of sufficient nutrient supply [26]. Usually SPM concentration in Kandalaksha Bay (0.3–0.6 mg/L) was close to that in the Basin because of low particulate river runoff [4, 5].

5.1.1 Seasonal Variability

Broadly, we revealed seasonal variability is most expressed in the Dvina and Onega Bays (influenced by river runoff) and least expressed in the Kandalaksha Bay and in the Basin [10]. Low SPM concentrations were reported for July–August, while high ones were observed for May and often for September. The width outflow current in the Dvina Bay (where transformed river water is traced by SPM, temperature, Chl-a, and dissolved organic matter on the images of MODIS-Aqua) is characterized by seasonal and interannual variability, and this is verified by the data from paper [21]. In the Onega Bay, the highest SPM concentration is observed most often in September and likely caused by strengthening from storm-induced mixing [9].

In general, the spatial and temporal variations in the SPM concentration in the White Sea are directly (mineral particles from the catchment area) or indirectly (diatoms blooming due to supply of biogenic elements) caused by river runoff.

The SPM concentration in the Mezen Bay (May–September) is usually high (about 2 mg/L and higher), which is mainly caused by coastal and bottom abrasion and the most powerful tidal mixing (flow velocity up to 250 cm/s, tide height up to 9.8 m) at shallow depths (<10–50 m) and partly by the influence of the Mezen River runoff.

The data on the SPM concentration in winter (under the ice) was quite poor. At the end of hydrological winter (e.g., in the end of April 2003), it varies from 0.2 to 1.6 mg/L. The highest concentrations were reported in the Basin, as a result of enrichment surface water by biogenic particles (usually diatoms).

5.1.2 Interannual Variations

The greatest amplitude of the average annual variability in the SPM concentration was revealed in the Dvina, Onega, and Mezen Bays and in the eastern part of Gorlo–Voronka area affected by river runoff. However, the greatest relative difference between the average annual values for different years was 18% (the significance value is 0.05; confidence probability is 95%) [10]. The differences between the maximal and minimal average annual concentrations were statistically significant only for the Kandalaksha and Mezen Bays. The minimal average annual SPM concentration in the entire sea was observed in 2007, the year of the lowest sea-ice extent in the Arctic marginal ice area. Changes in ice conditions in the Barents–Kara Sea region appeared to be primarily forced by ocean heat fluxes during winter [53].

Based on the satellite data, the interannual linear trends of sea surface temperature, SPM concentration, Chl-a content, and CDOM absorption have been estimated; these estimates have shown no significant trend for the discussed period of 2003–2010 [38].

A significant correlation has been revealed between the average annual SPM concentrations in the White Sea as a whole, the eastern part of the Gorlo–Voronka region, and the Dvina Bay ($r = 0.7$, $n = 8$). This correlation indicates the determining role of the Severnaya Dvina River inflow in SPM dynamics of the White Sea. Additionally, a relationship has been found between the average annual values of SPM concentration in the western and eastern parts of the Gorlo–Voronka region ($r = 0.75$, $n = 8$); this relationship is caused by intensive turbulent mixing and lateral suspended particulate transport in this region [24].

Finally, we would like to conclude that the SPM concentration in the White Sea's surface active layer is about 1 mg/L, on average. The main sources of SPM in the White Sea have been found: mineral particles of river runoff origin and marine phytoplankton. First of all, they are particles supplied from the catchment areas with the river runoff (the most intensive flow is in May) and only partially supplied from melted ice cover (usually in April). Abundance of phytoplankton is caused by a combination of many abiotic factors, including the supply of nutrients with river runoff and melted ice. The local hydrological conditions promote the formation of high spatial variations of the SPM distribution.

We found out a relationship between the dynamics of the average annual SPM concentration in the White Sea as a whole and in the constant outflow current which transports water of the Severnaya Dvina River along the Dvina Bay to Gorlo Strait coast. We can suppose that seasonal and annual variability in the SPM concentration could decrease during climatic warming in the Arctic.

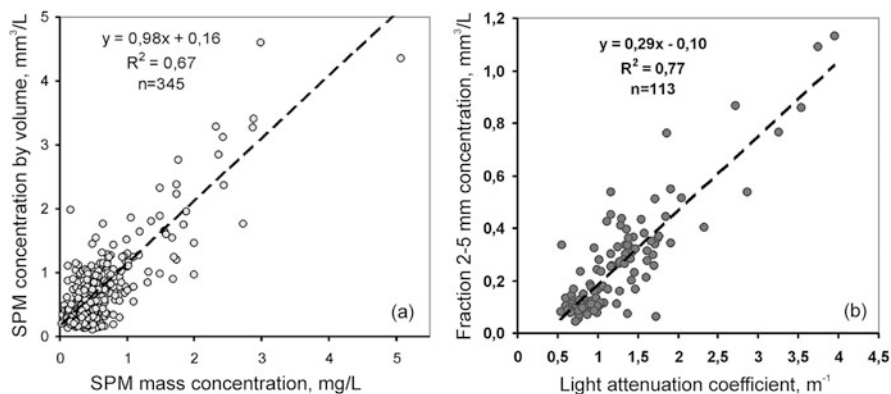## 5.2 SPM Concentration by Volume in Surface Layer

The SPM study in the White Sea with the Multisizer 3 (Coulter counter) device demonstrated a good consistency with the data obtained by the traditional vacuum filtration method and optical measurements (Fig. 6).

The SPM concentration by volume in the White Sea varied from 0.2 to 5 mm^3/L and approximately 1.0 mm^3/L in average. The highest concentration was influenced by the river runoff area. SPM concentration by volume was about 5 mm^3/L in adjacent to the Severnaya Dvina River mouth (Table 1). The lowest one was observed in the upwelling nearby the Solovetsky Archipelago where the low primary production and phytoplankton abundance were detected.

The distribution of SPM concentrations by volume in the White Sea corresponds to the main features in the distribution of mass concentrations. However, SPM concentrations by volume are a reliable proxy for biogenic (phytoplanktonic) particles, whose sizes vary from 2 till 200 μm commonly. In addition, there are different approaches to measurement procedures.

We have made a comparison of the SPM concentration by volume (0.5–5 mm^3/L) and the phytoplankton abundance (0.1–3.7 mm^3/L) [52]. According to our calculations, percentage of phytoplankton in total SPM varied in the different regions of the White Sea: 27% in the Dvina Bay nearby the Severnaya Dvina River mouth, 40% in the Basin, and 65% in the Kandalaksha Bay. The content of terrigenous particles decreased with distance from the river mouths, although remains quite high (till 40%) in the open water areas.

In the coastal waters, we observed significant variations in SPM concentrations (from 1 to 5 mm^3/L in the marginal filter area of the Severnaya Dvina River). These variations depend on the river runoff volume, the tidal phases, and the water salinity. The position of the marginal filter is limited to isohalines of about 0.2 and 24 psu [28].

Fig. 6 The relationship between SPM concentration by mass and volume (**a**) and between light attenuation coefficient and fine fraction of the SPM (**b**) in the White Sea

Table 1 The SPM concentration in the surface layer of the White Sea after spring flood in June 2003

	SPM concentration by volume, mm³/L	SPM mass concentration, mg/L	Total number of bacterioplankton, th. cells/mL
The inlet part of the Dvina Bay			
Variations	3.1–4.6	2.1–6.5	430–588
Mean	3.8	4.6	487
Sample number	4	5	3
Dvina Bay			
Variations	0.7–2.9	0.4–3.4	55–219
Mean	1.4	1.3	138
Sample number	29	28	16
Area of Solovetsky Archipelago			
Variations	0.4–0.9	0.4–1.2	64–96
Mean	0.6	0.8	81
Sample number	12	12	4
Kandalaksha Bay			
Variations	0.6–1.3	0.3–0.9	110–160
Mean	0.9	0.5	138
Sample number	9	9	4
Basin			
Variations	0.5–2.0	0.3–1.2	49–240
Mean	1.0	0.7	158
Sample number	22	22	8
Mean for the sea proper (excluding the inlet part of the Dvina Bay)			
Variations	0.4–2.9	0.3–3.4	49–240
Mean	1.0	0.9	134
Sample number	72	71	36

The SPM concentration in the Severnaya Dvina delta reached 5.8 mm³/L where the water salinity was about 5 psu (coagulation and adsorption stage of the marginal filter). As the water salinity increased to 20 psu, a decrease in the SPM concentration was observed. It is remarkable that, in the mouth areas of the large Siberian rivers (Lena, Yenisei, Ob, Pur, Taz), high gradients in the SPM concentration decrease were established, which is approximately similar to the marginal filter of the Severnaya Dvina River within the hydrological front under salinity of 20 psu [54]. The sharp increase in the SPM concentration by volume was revealed in waters with salinity exceeding 23–24 psu in the area located immediately beyond the boundary of the saline front due to an increase in phytoplankton share in total SPM [28].

6   SPM Concentration by Mass and Volume in Water Column

The vertical distribution of SPM in the deep part of the White Sea, as well as the hydrological structure, has a three-layered structure. There are two maxima of the SPM concentrations at the surface (the surface active layer above the pycnocline) and at the near-bottom layer (nepheloid layer) separated by intermediate more clear water. Vertical stratification depends on heating intensity and freshwater input mostly in summer and salinity distribution basically in spring [23].

The temperature and density stratification of the water column and, as a consequence, SPM stratification are most pronounced in the deep part of the sea in summer. Density deformation of the vertical structure of the water column in summer forms a so-called liquid bottom, where a significant part of samples for SPM study was collected (usually at the layer of 5–20 m). The pycnocline (thermocline) depth usually ranges from 11 to 22 m. Subsurface pycnocline (close to water surface of 5–10 m) is formed more rarely near the surface of the sea. Beneath the pycnocline the SPM concentration decreases by 3–4 times (Fig. 7).

In summer, the intermediate more clear layer (deeper than 40 m) consists of warm and cold waters of advective origin [23]. The SPM concentration reached 0.2–0.3 mg/L in this layer that is close to the same concentration in the Barents Sea [50].

In spring (April 2003), the thickness of the upper (winter convective) layer came to 20–50 m (it is the boundary of the cold intermediate layer). The SPM concentration in water column varied 0.5–0.6 mg/L (deep sea areas) and increased till 0.8–1 mg/L just in the thin near-surface layer (spring phytoplankton bloom). The particles accumulated above and within the pycnocline during summer (when the strong seasonal stratification observed) begin to float and spread within the winter convective layer. The SPM didn't sink, since this is prevented not by pycnocline (like in summer) but by a gradual increase in water density with a depth below the thermocline [24].

A weak stratification or even a homogenous vertical distribution of SPM, temperature, and density was revealed in the Onega and Mezen Bays.

The thickness of the near-bottom nepheloid layers in the White Sea ranged from a few meters to a few tens of meters (10–20 m, on average). The SPM concentration in the nepheloid layer of the White Sea (up to 5 mg/L in the shallow area) is close to values in the nepheloid layer of the Barents Sea. However, the turbidity and thickness of these layers are usually much lower than in the Kara, Laptev, and East Siberian Seas [49, 50].

We revealed a powerful bottom nepheloid layer nearby the eastern coast of the Dvina Bay (outflow current) with SPM concentration till 5 mg/L in summer. The next one is located in the Gorlo Strait where the SPM concentration of the bottom nepheloid layer was always high (till 3 mg/L) in any tidal phase.
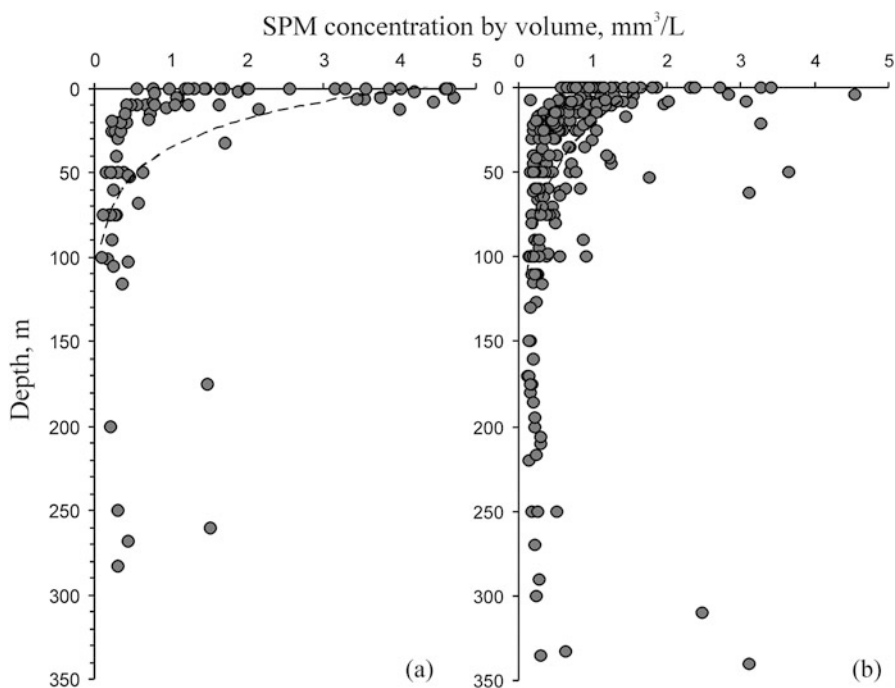
Fig. 7 The distribution of SPM concentration by volume according to the White Sea depth in June, 75 samples (**a**) and August, 398 samples (**b**)

Since a relatively clarity of the Barents Sea waters inflow along the Tersky Coast to the White Sea, the SPM stratification there differs from the other regions. Here, the presence of powerful temperature inversions (up to 2°C) and turbidity fluctuations with depth were observed.

Waters with the similar T°–S indices were found in the deepwater part of the Basin in June 2003 and in the Gorlo Strait at the end of the hydrological winter, April 2003 [24]. The near-bottom water's hydrophysical characteristics in June fully coincided with the winter observations. The SPM concentration in the near-bottom layer (250–280 m) of the Basin in June corresponded to its values detected in this water mass in the Gorlo Strait in April (0.7–0.9 mg/L and 0.3 mm³/L). These concentrations were slightly higher than that one in the intermediate water mass, where they did not exceed 0.3 mg/L or 0.1–0.2 mm³/L. It may be caused by the phenomenon of cascading. It is assumed that the cascading has an advective and gravitational origin [4].

Some full-depth vertical transects are displayed in Figs. 8 and 9. SPM distribution is characterized by vertical stratification with maximal concentration in the upper active layer (10–15 m) according to the density and temperature structure.
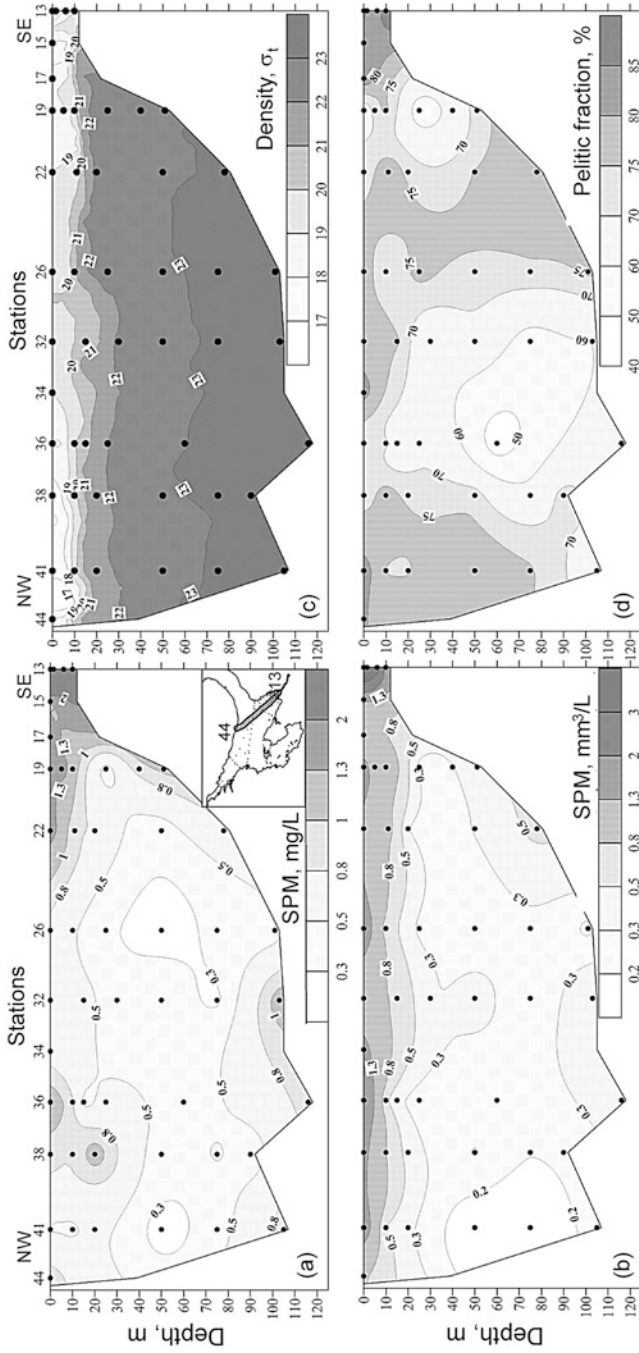
Fig. 8 The full-depth cross section from the Severnaya Dvina River mouth till the Tersky Coast in June 2003: (**a**) SPM concentration by mass and (**b**) volume, (**c**) water density, (**d**) pelitic fraction content
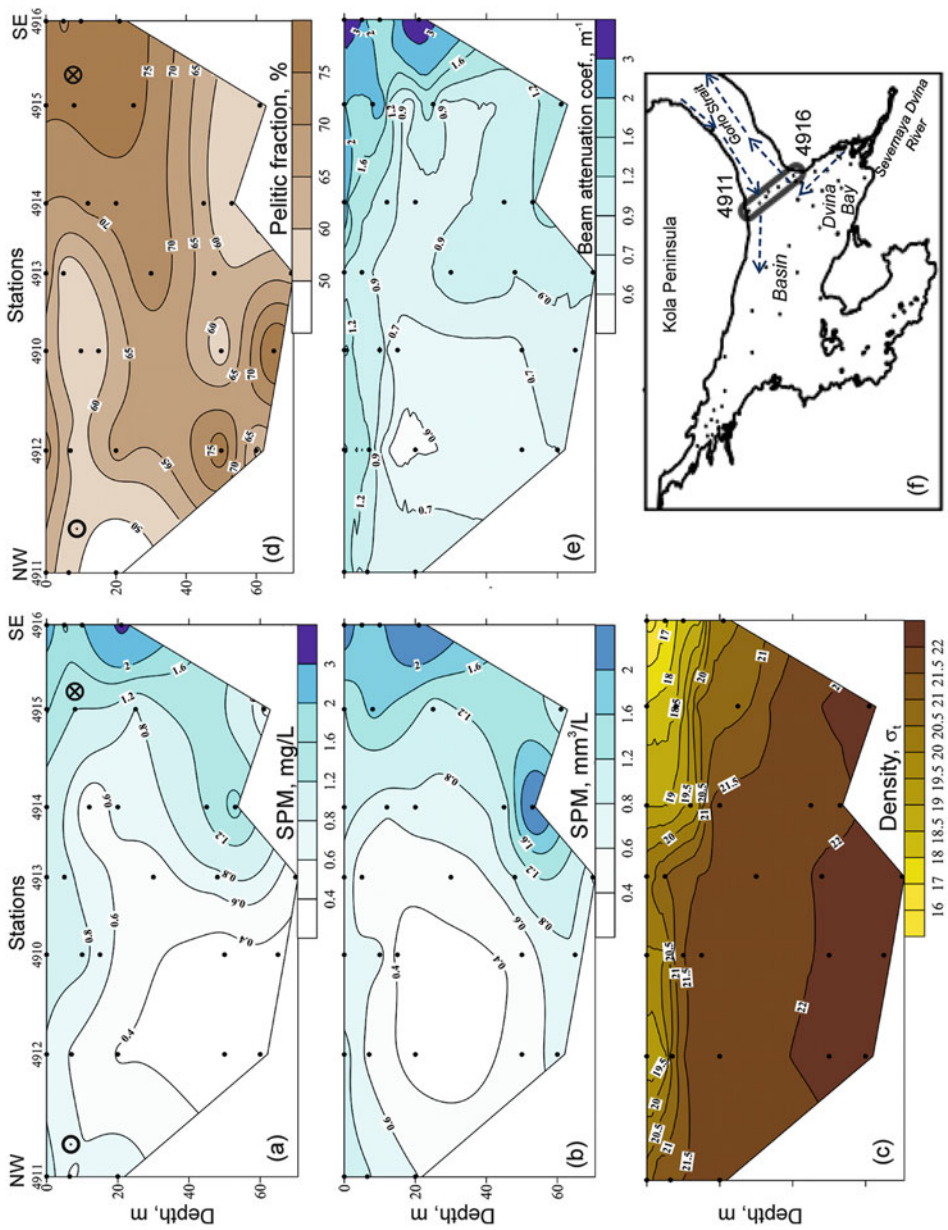
Fig. 9 The full-depth cross section in the southern part of the Gorlo Strait, August 2003: SPM concentration (**a**) by mass and (**b**) by volume, (**c**) water density, (**d**) pelitic fraction content, and (**e**) beam attenuation coefficient. Section location and major currents are shown in (**f**)

For isolines of SPM concentration and density, a quasi-horizontal distribution pattern is typical, reflecting a sharp thermocline with an axis on the 15 m depth and a coexisting halocline (Fig. 8).

Sometimes we observed subsurface lenses of turbidity waters in the areas close to hydrological fronts. Some kind of the turbid lenses were observed in the Kandalaksha Bay at the layer of 50–150 m in August and June. This is a consequence of the widespread phenomenon in the White Sea of interlayer transport, a related process to the so-called cascading – the sliding down of water off the slope in winter and the movement of water from the surface to a layer of 20–60 m in summer [4, 24].

Turbid waters nearby the Tersky Coast obviously resulted from some physical processes such as a tidal mixing and coastal upwelling.

One of the most interesting transects crossed the Gorlo Strait is shown at Fig. 9. One can clearly see the transport of transformed river water enriched in SPM and relatively clear water inflowed from the Barents Sea.

7 Chlorophyll "a" Concentration

The average concentration of Chl-a in the photic layer usually exceeds 1 µg/L (reaching 9 µg/L, and sometimes 21 µg/L, in the shallow inlets of the bays), i.e., the threshold for characterizing the waters as eutrophic ones. The thickness of photic layer in the White Sea is 10–15 m on average. In summer, the maximal concentration was observed in the surface water layer (about 0–12 m), sometimes in the subsurface layer of 0–5 m. The maximal annual variability of Chl-a concentration in the photic layer was observed in the Dvina Bay [55].

According to the optical measurements both in situ and by satellite scanners, the depth of 1% of PAR varies from 7.0 to 8.8 m, and 0.1% of PAR was found at 11.2–14.5 m, respectively [43]. The water masses of the White Sea are characterized by high solar light absorption comparing to the Barents Sea and the Kara Sea. This difference is primarily preconditioned by the content and composition of both the SPM and CDOM; the concentration of the latter is extremely high in the White Sea. The maximal photosynthetic activity in the White Sea was observed in the quite narrow surface water layer. Our data allowed us to conclude that photic layer in the White Sea is approximately less than 15 m depth; it varied from 2–5 m (Dvina Bay) to 20–25 m (deep part of the White Sea).

The average concentration of Chl-a in photic layer in June exceeded the values of July nearly twofold and more than twofold in August. In most of areas of the White Sea, in the late summer, the phytoplankton biomass was lower compared to spring and early summer. The studies of primary production in late August of 2001–2007 [31, 52] also support this observation. The results evidenced the oligotrophic status of the water masses in the central White Sea and the open part of the Kandalaksha Bay. The water masses of the Dvina and Onega Bays may be characterized as oligotrophic–mesotrophic in August. The minimal concentrations of Chl-a in the

White Sea are referred to the start and the end of the productive season, i.e., April and October, respectively.

When the water column is stratified well (deepwater area of the sea), a maxima of Chl-a concentration was observed above pycnocline, which usually coincided with the halocline; this refers to the pattern of the phytoplankton vertical profile.

Seventy percent of the phytoplankton biomass and Chl-a was concentrated in the photic layer (July 2009) [26]. Subsurface Chl-a maximum (3–5 m) was observed in the open water area of the Dvina Bay. There was surface Chl-a maximum in the area subjecting the Severnaya Dvina River flow (0–1 m) and in the Onega Bay and the Basin (0–3 m).

Subsurface Chl-a maximum was often detected in the photic layer; there was a tendency to increase the nitrate concentration as it approached the upper boundary of the thermocline (July–August 2014) (Fig. 10). The highest concentrations of nitrates were confined to the under thermocline water layer (up to 9 μg-at N/L).

The subsurface Chl-a maximum was observed in the 3–12 m water layer in August 2013 at most sites of the White Sea [56].

The highest biomass of phytoplankton and, accordingly, the concentration of Chl-a were usually recorded in weakly stratified waters, where nutrient supply is a result of tidal mixing. In the sharply stratified waters of the sea during the summer season, the supply of nutrients to the photic layer is limited, and the abundance of phytoplankton was low. Probably one of the significant factors determining the spatial heterogeneity of phytoplankton can be the penetration of freshwater lenses from the Dvina Bay to the Basin of the sea [26].

Below the pycnocline, the concentration of Chl-a decreased greatly with the sea depth increased. A decrease in the Chl-a concentration down to 0.5 μg/L and lower was observed in the intermediate water masses (depth range of 20–60 m, on average 50 m) and near-bottom water masses originating from the Barents Sea.

The concentration of Chl-a may reach extremely high values of 1–2 μg/L in the intermediate and near-bottom water masses (depths of 30–90 m) in the area of the structural hydrological front in the southern part of the Gorlo Strait. The phytoplankton biomass here was also high, which refers to the summer phytoplankton bloom [26].

Generally, the concentration of Chl-a in June–July varies from 0.05 μg/L (near-bottom water layer) up to 2.5 μg/L (surface-mixed photic layer), reaching 9 μg/L (and sometimes 21 μg/L) in the shallow inlets of the bays. The spatial distribution of Pheo-a was also patchy, as is observed for Chl-a. The content of Pheo-a varied from 0.6 to 100%. Alongside with that, a high share of Pheo-a (more than 50%) was usually observed in the intermediate and near-bottom water masses and also in the upper water layer of the river runoff and in the area of the salinity fronts.

So, the concentration of phytoplankton varies greatly in different areas of the White Sea during summer [26]. It was found that the distribution of Chl-a was also not uniform. The riverine inflow and hydrodynamics of the sea (hydrological fronts and increasing of the vertical gradients of water density) have the most pronounced effect, while water heating has a less effect.

The assessment of the monthly average of Chl-a concentrations in the different areas of the White Sea obtained by satellite observations evidences the similarity of
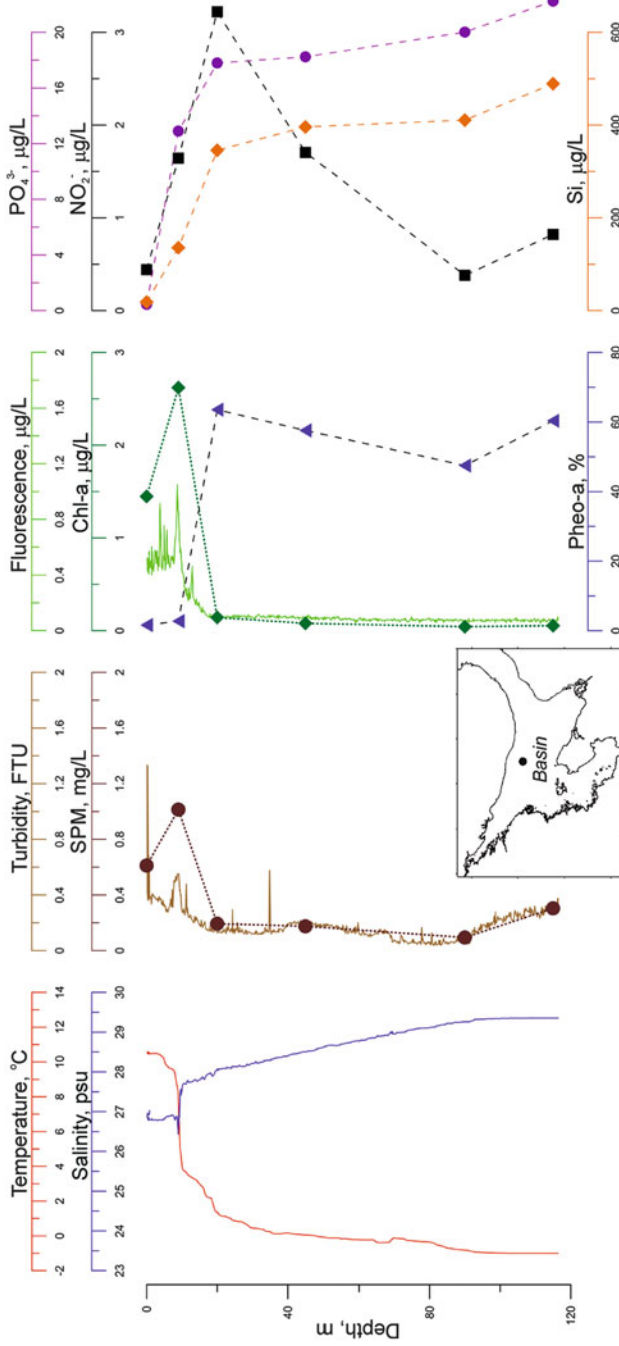
Fig. 10 The vertical distribution pattern of temperature, salinity, turbidity, SPM, and Chl-a concentration, Pheo-a content, and nutrients concentration in deep part of the White Sea, the northern area of the Basin. The sea depth is 120 m

the dynamics of Chl-a concentration and the SPM concentration [55]. However, the Chl-a dynamics is smoother. On the one hand, the concentration of Chl-a and SPM in the photic layer is controlled by the entrance of allochtonous matter with riverine discharge, which predetermined their similarity. On the other hand, the concentration of Chl-a (proxy of autochthonous matter) depends on the primary production intensity. The PAR depth and enrichment of the surface water layers in nutrients due to the mineralization of POM in the pycnocline smooth the seasonal variability of the Chl-a concentration during summer low-water in the catchment area.

The highest Chl-a concentrations are in the Onega, Dvina, and Mezen Bays, which are preconditioned by the riverine supply of nutrients.

The influence of the wind stress on the vertical distribution of Chl-a concentration was well pronounced in the photic layer. After the storm (up to 4 on the Beaufort scale, with a wind speed up to 16 m/s, July 2010), the average concentration of Chl-a in the upper layer in the Dvina Bay decreased by approximately 1.5 times. The SPM and Pheo-a concentration were correspondingly (by the same amount) [55]. According to the satellite images, the wind stress had a significant effect on the Chl-a distributional pattern for the most area of the White Sea (Fig. 5).

The concentration of Chl-a in the White Sea is significantly higher compared to the Barents Sea and the Pechora Sea and is quite similar to the Kara Sea, which is also affected strongly by intensive riverine discharge.

Despite the fact that Chl-a constitutes an insignificant part of the SPM (0.1–1.0% of dry weight), a positive correlation was found between these parameters, which becomes stronger in the areas affected by riverine discharge ($r = 0.8$ in the marginal filter of the Dvina Bay, $n = 13$). The correlation coefficient may vary and even reach zero depending on the phenological season.

A well-pronounced direct correlation between Chl-a and POM concentration was found for the different water masses of the White Sea [55].

These relationships are primarily predetermined by the same factor, i.e., by the riverine discharge, which carries both SPM and nutrients to the White Sea.

The typical full-depth vertical distribution of Chl-a are displayed in Fig. 11. The effect of the outflow current from the Dvina Bay was clearly shown. The high concentrations of Chl-a in a thin photic layer related the current were well illustrated (Fig. 11).

Finally, we would like to conclude that variability of monthly averages of Chl-a concentration, as calculated by the satellite data, evidences the similarity of seasonal dynamics of Chl-a and the SPM concentrations.

The maximal concentration of Chl-a (3–9 μg/L) was registered during the summer period at depths usually of 0–5 m and at deeper layers till 10–12 m. Most of the POM was synthesized by the phytoplankton during photosynthetic processes in a relatively narrow surface water layer of about 0–12 m, i.e., in one of the most biochemical active water layers.

Subsurface Chl-a maximum (3–12 m) was observed in well-stratified waters in summer. Surface Chl-a maximum was registered at the hydrological fronts, in the tidal mixing areas with low sea depth and in the river lenses (enriched with nutrients)
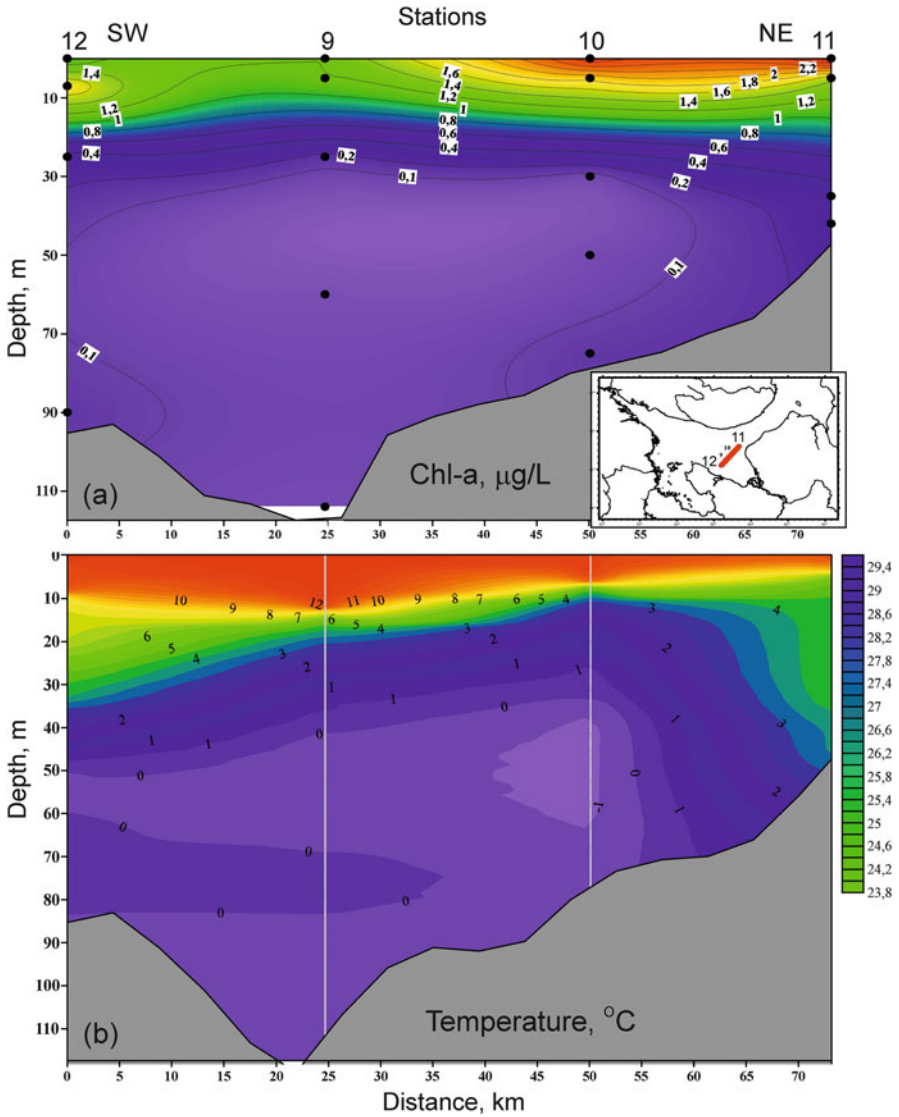
Fig. 11 The full-depth cross section of Chl-a concentration (**a**) and temperature (**b**) in the outer part of the Dvina Bay in July 2012

penetrated to the open water area as a result of wind stress. We generally found that both increased pigment per cell and cell numbers of phytoplankton in the White Sea.

8 SPM Grain-Size Distribution

The SPM, as a rule, has micron and submicron sizes. The SPM mostly consist two fractions: (1) 0.4–10 μm, pelitic, and (2) >10 μm, fine and coarse silty [57]. The most abundant particles in seawater is till 20 μm in size [58]. Sandy fraction (separate particles of detritus, secondary particles – coarse aggregates) is less common in the sea. This fraction is unstable in terms of sedimentation, and it forms the basis of vertical fluxes of sedimentary matter. The fractions here and further are distinguished according to the classification of Bezrukov and Lisitsyn [59] for marine bottom sediments, accepted in IO RAS, and underlying all maps of bottom sediments in the *Atlas of the Oceans* published in 1974–1980, USSR.

The SPM grain-size of the White Sea is formed under two main sources – lithogenic and biogenic ones – which are in complicated interactions in space and time. In this connection, the grain-size diversity of the SPM is due, first of all, to the different contributions of phytoplankton and riverine mineral particles. There are 12–25 million particles/L in the White Sea and 5–6 million particles/L in the open Atlantic Ocean.

The most common type of the SPM is silty–pelitic polydispersity, since the content of each fractions is rarely exceeds 50% (by volume).

The SPM of the White Sea was characterized by medium sorting as a rule. Median diameter (Md) of the SPM varied from 3 to 11 μm. Similar values were obtained for other seas of the Arctic as well. Due to the fact that the SPM is usually polydispersity, Md can deviate significantly from the modal diameter.

In the Arctic shelf seas such as White, Kara, and Laptev, the increased content of pelitic fraction (≥50%) is a proxy of the transformed river particulate flow (Figs. 8 and 9). The content of lithogenic particles and the content of pelitic fraction decreased with the distance from the river mouths.

The high content of pelitic fraction tends to the regions of river water discharge in the White Sea. Thus, the content of fine particles <5 μm usually exceeded 50%, and their Md was less than 5 μm. The sorption capacity of the SPM was maximal in the area of the Severnaya Dvina River marginal filter and decreased in the direction to the central parts of the sea. It is well known that the high dispersity of the SPM increases the sorption activity of the particles and may promote the development of bacteria. We showed that, in the White Sea, more than 60% of the total number of bacterioplankton (TNB) consisted of cells attached to detrital particles (Table 1) [30]. Each of these particles, as a rule, is saturated with bacteria, mostly in the form of rods and cocci.

The grain-size transformation of the SPM in the marginal filter of the Severnaya Dvina River was studied in August 2005 [30]. At the first stage, in the earliest steps of mixing river and seawater (salinity of water from 0.2 to 2 psu), the sandy and silty fractions were deposited. The decreasing of SPM concentration was accompanied by a twofold decrease in TNB (from 360 to 170 th. cells/mL).

Coagulation and sorption stage of the marginal filter were revealed between isohalines of 2–15 psu. Here, the principal sorbents are iron hydroxides, organic

matter, clay minerals, and siliceous and calcareous organism remains. At this stage, the greatest specific surface area of the SPM, according to the data of the laser analyzer, corresponded to its lowest Md and the maximal value of the TNB (520 th. cells/mL). Bacteria settled over the newly formed aggregates. In addition, at water salinity of 2–15 psu, the extinction of both freshwater and marine plankton occurs; as a result, DOM is released to provide the development of bacteria.

At the third (so-called biological) stage (water salinity 15–24 psu), the silty fraction prevailed in SPM due to phytoplankton development. It is shown that phytoplankton bloom is usually observed along the outer boundary of the marginal filter, where water salinity reached to 23–24 psu. The decline of the TAM (till 150 th. cells/mL) is caused by decrease in the amount of detritus (to which the development of bacterial cells is strongly related) and by the intensive formation of alive organic matter, which limits their development by the food and competitive interrelations.

So, we established that the water salinity is the main factor that controls the changes in the grain-size distribution and composition of the SPM in the marginal filter. The concentration by volume of fine particles (2–5 μm) and water salinity demonstrated negative correlation between each other ($R^2 = 0.86$, $n = 24$).

The largest variations in the SPM grain-size composition were found in the photic layer of the White Sea (about 0–15 m). The pelitic fraction (2–10 μm) prevailed in the surface water layer in June. The content by volume of the fraction reached 70–90%. During this period, the SPM can be called predominantly pelitic.

The content of pelitic fraction (40–70%) in surface layer was lower in August than in June. But maximal content of the fraction was always confined to the Severnaya Dvina River mouth. The Md of SPM in the outflow current was 5–7 μm which marked the trajectory of the current.

We revealed the influence of tidal phase on SPM grain-size composition. During the high tide, the content of the pelitic fraction decreased by almost twofold, while the silty fraction increased also by twofold in comparison with that during low tide in the Dvina Bay. The grain-size curve had bimodal distribution during high tide: 3 and 12 μm. The second peak connected with diatoms had been smoothed during low tide. The SPM of the transformed Barents Sea waters was characterized by a lesser sorting of particles than the river particulate matter during low tide.

The vertical zonality is reflected in SPM grain-size distribution and explained by stratification of the water column. In the surface layer (above pycno- and thermo-cline), the SPM grain-size is characterized by bimodal distribution: the first peak corresponds to the pelitic fraction, while the second peak coincides to the fine silt fraction. Under the pycnocline (~10 m), the content of silty fraction sharply reduced and the share of fine particles increased. Md was often several times reduced under the pycnocline layer in comparison with the surface water layer. This implies that the barrier effect of the pycnocline is reflected in the SPM grain-size according to hydraulic weigh, size, and composition. This layer, which is also referred to as "the liquid bottom," represents a trap for biogenic particles firstly (especially for plankton remains, which density is close to the density of the surface water). A bacteria growth is noted above the vertical density gradient. The abundance of

bacteria most often features a peak immediately beneath the SPM maximum, i.e., in the layer with the maximal content of detritus.

In the stratified water column, the content of pelitic fractions (2–10 μm) changed a little. This is so-called basic particles dispersion background of seawater.

Thus, extremes in the SPM distribution are governed by both the grain-size of primary material (sources) and trend of its transformation in water body.

Particles disperse system in the seawater is unstable. Coagulation rate of submicron particles is several orders of magnitude higher because of the Brownian motion as compared with that of their coarser counterparts [14]. Precisely this difference in coagulation rates is likely responsible for the aggregation of submicron particles and appearance of peaks in the fraction of 3–6 μm in deep water layers.

The content of silty fraction increased (till 60%) in the near-bottom nepheloid layer (particles and aggregates). The TNB growth in the near-bottom layer was often related to the nepheloid layer. This phenomenon is caused by the increase in the contents of the products of the OM destruction at the bottom; its decay also proceeds in the surface layer of the bottom sediments.

There is no recent sediments deposition in the area with high content of silty fraction and large Md (>10 μm) of the SPM in the nepheloid layer. Thus, glacial marine sediments and ridges of glacial origin are spread along the eastern coast of the Dvina Bay in the area of the outflow current. The less content of silty fraction and small Md (~5 μm) of the SPM in the near-bottom layer occurred in the areas with marine Holocene sediments of nepheloid genesis [57].

9 General Properties Indicative of SPM Origin

The SPM is a fine multiphase and complex object for studying; it is represented by a mixture of biogenic particles (phytoplankton and detritus), single mineral grains, aggregates, and layered silicates.

9.1 Main Mineral Composition

The share of the clay minerals in the SPM was 40% and even more in the White Sea [60]. In other words, the crystallic phase of SPM in seawater was represented by 50% clay minerals. Illite kept the dominant position (35–57% of the sum of the clays in the fraction of <0.01 mm). The high content of illite was a characteristic of the fine particles (both the pelitic and submicrons fractions of the SPM).

Smectite was represented by relatively high content (8–30%); it is characterized by higher dispersity and is mostly found in the subcolloidal fraction (<1 μm). This mineral is supplied with the Severnaya Dvina River runoff and accumulated in the finest muds at depths of more than 100 m.

The content of chlorite and kaolinite varied from 15 to 27%. Mixed-layered minerals usually comprised an insignificant admixture in the SPM (from trace amounts to 5%).

The similar composition of the clay minerals of the SPM was a characteristic of other Arctic shelf seas (Kara Sea and Laptev Sea), which are affected by the large lowland rivers crossing several natural zones [61, 62].

The fine fraction of the clastic minerals is found in every sample, both in the open sea areas and in the coastal waters, and in a significant amount. Among them, quartz and feldspar provide basic background (up to 50%), and quartz usually dominates. The smallest debris of these minerals reached the open sea areas and enriched the pelitic fraction of muds during the sedimentation process. This evidences the partly mechanical separation of the SPM in the dynamic system of the White Sea.

9.2   Content of Particulate Si, Al, P, and Organic Carbon (POC)

The content of total particulate Si in the photic layer of the White Sea varied from 1.8 to 26%. High content of total particulate Si was observed in the areas close to the river mouths and coasts subjected to river inflow. The content of lithogenic particles in these areas was high (30–92%), while that of biogenic Si (SiO_{2am}) varied from 7 to 21%.

We revealed the regular decrease of Al content with the distance from the coast. It is mainly associated with feldspars and clay minerals. The content of Al in the surface water layer varied from 0.3 to 7.9% averaging 1.3%. The mean value was close to the mean Al content in the SPM of the Baltic Sea (0.5–1%) and much less than in the Kara Sea (4%) [49]. Al was mainly accumulated in the pelitic fraction of the SPM as a component of the clay minerals and fine debris of feldspar. Al accumulated mostly in the pelitic fraction of the SPM (Fig. 12); its content increased exponentially in accordance with increase of the lithogenic pelitic fraction (<10 μm) [28].

The Al content in SPM of about 1% or less is a typical value for the White Sea central part (the Basin) and open areas of the Kandalaksha Bay. Higher Al contents (till 3.3%) are typical values for the transitional river–marine type of SPM; these values characterize the rest areas of the sea.

The high content of total particulate Si, as a rule, corresponded to an increased content of Al. The SPM of the White Sea was characterized by a direct linear correlation between Si and Al (Fig. 12). The content of lithogenic particles reached 69% in the outflow current (the transformed Severnaya Dvina River waters). We obtained the maximal content of lithogenic material (87%) in the bottom nepheloid layer close to the eastern coast of the Dvina Bay.
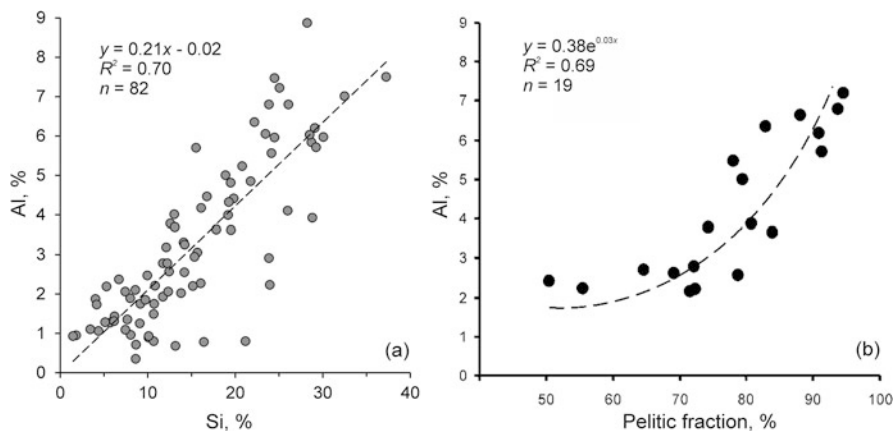
Fig. 12 The dependence of Al content in SPM from Si (**a**) and pelitic fraction (2–10 μm) (**b**) content in the White Sea in summer

The total Si/Al ratio in the SPM of the White Sea was close to that in the upper continental crust (3.3–3.8) in the regions subjected to the river inflow. This value was higher in the western part compared to the eastern ones.

The Severnaya Dvina River catchment area is located within the natural zones where a stage of the chemical denudation predominates over mechanical and acidic weathering stages. Among other components, Fe^{3+}, Al, and Ti are leached from the rocks [25]. At these conditions, the bulk of the particulate Si occurred not only as a component of clay minerals but also in the form of quartz. Because of this, the SPM and bottom sediments are enriched in Si in the White Sea.

High content of P (0.5–1%) was revealed in the Basin and Kandalaksha Bay. Nearby the sources of the lithogenic material supply, the P content decreases noticeably (to 0.1%).

The content of POC was 14% on average, varied usually from 5 to 30%. The average content of POC in the marine SPM was twofold higher than in the riverine SPM. The lowest content of POC (10%) was measured in the area of the Severnaya Dvina River mouth. We identified that POC content decreased logarithmically with increasing of the lithogenic material. We revealed the negative correlation between particulate Al and POC content.

So, POC in the White Sea had as a rule mostly autochthonous genesis rather than allochthonous. Its content depends on the composition and distribution of primary producers, i.e., phytoplankton. The content of POC in the plankton varied from 27 to 46% (35%, on average) [63]. The maximal content of POC was typical for the Kandalaksha Bay [21, 63].

In the liquid bottom layer of stratified waters, the separation of the major part of the biogenic elements (C, N, P, and others) from the solid (mineral) parts of organisms is accompanied by a growth in the bacteria abundance. It is established that the high bacterial production in the layer of the pycnocline resulted from the

formation of microzones enriched in nutrients around the decaying phytoplankton cells. A subsurface maximum of POC was caused by the accumulation of detritus, and bacterioplankton was often observed in the White Sea at depths of 10–20 m.

We found a positive correlation between the SPM mass concentration and the POC content, as well as between SPM concentration by volume and POC content. Then we studied the relationship between the POC concentration and the different SPM fractions. It turned out that the best correlation was characteristic for the finest of the studied pelitic fractions ($R^2 = 0.8$, $n = 54$). Consequently, the POC concentration in the water column of the White Sea is primarily related to the distribution of fine particles less than 10–8 μm.

The content of PIC was insignificant and represented mostly by dolomite (to 5%). Calcite and aragonite were of secondary importance; their content was about 1–2% or was beyond the detection limits.

9.3   Isotopic Composition of POC

Isotopically light POC [$\delta^{13}C_{POC}$ to −30.0‰ (PDB)] is transported to the White Sea from the coast mostly with river runoff. The Severnaya Dvina River water has a hydrocarbonate composition with the predominance of the sum of ions Ca^{2+} and Mg^{2+} over the sum of Na^+ and K^+. Isotopically heavy POC [$\delta^{13}C_{POC} = −18...$ –22‰ (PDB)] is a part of the phyto- and bacterioplankton biomass [18, 22, 31, 56].

Values of $\delta^{13}C_{POC}$ varied from −25.7 to −27.4‰ in the open water area of the Dvina Bay, and it was lighten to −28.1... −29.8‰ in the shallow costal area (July 2010). Allochtonous POC prevailed just on the sites close to the coast with sea depth of 12–26 m [56]. The value of $\delta^{13}C_{POC}$ (−23.1... –26.7‰) in the photic layer of the Dvina Bay in August 2014 were close to the data obtained in July 2010 [56]. These values indicate a mixed composition of POC for the larger part of the sea, which is evidenced by different proportion of autochthonous (phytoplanktonic) and allochthonous (lithogenic) material. It seems that the isotopically light POC was not supplied into the deep parts of the White Sea in July–August 2010 and in 2014. It should be noticed that isotopically light POC ($\delta^{13}C_{POC} = −28.1...$ –29.8‰) prevailed in the White Sea proper just at the end of August 2006 [31].

It was shown that concentration and composition of POC as well as DOC (including a colored dissolved organic matter) were subjected to the significant annual and seasonal variations [21, 28, 40, 41].

10   Concluding Remarks and Outlook to Future Researches

The SPM of the White Sea didn't pass the full mechanical and biological separation in the water body. The reason for this phenomenon would be the small volume of the sea (5,375 km^3) and the shallow sea depth (medium depth about 67 m) with the

significant annual volume of dissolved and particulate river runoff (230 km^3/year and 2,330 × 10^3 ton/year, respectively [25]).

The SPM concentration in the White Sea photic layer was about 1 mg/L (or about 1 mm^3/L), on average. The SPM concentration decreased exponentially in the area of the marginal filter. Only 30–20% of the river particulate matter pass through the marginal filter and enter the sea. The main factor which controls SPM concentration and composition in this area is water salinity.

Not surprisingly, the SPM concentration decreased in several times with the distance from the coast, i.e., outside the marginal filter area that is related to so-called circum-continental zonality, according to Lisitsyn [1]. The SPM distribution pattern was controlled by local factors such as the hydrological fronts (structural, salinity, estuary, etc.), tidal mixing, and wind stress.

We established that the SPM concentrations by volume are a reliable proxy for biogenic (phytoplanktonic) particles in the photic layer. According to our calculations, the share of phytoplanktonic particles in total SPM varied in the different regions of the White Sea from 27% in the inner part of the Dvina Bay (influenced by a huge river runoff) to 65% in the open part of the Kandalaksha Bay (small river runoff).

The primary sources of SPM in the sea have been identified. These were lithogenic particles of river origin and marine phytoplankton (as well as detritus). Aeolian, ice, and coastal abrasion particles were of a secondary importance. First of all, this is particulate material supplied from the Severnaya Dvina River watershed. The rock composition of the Severnaya Dvina River catchment area determines largely the lithogenic phase composition of the SPM. This is confirmed by smectite and quartz high content in the pelitic fraction, high particulate Al and Si content, and so on. This is a result of climatic zonality [1].

The Chl-a concentration (proxy for the phytoplanktonic particles) was pre-conditioned by the same factor as lithogenic phase, namely, by the riverine discharge, which transports not only solid load (suspended particulate matter) but also the dissolved nutrients. The huge content of colored dissolved organic matter (CDOM) in the river water and, as a consequence, high content of CDOM in the White Sea predetermined the quite narrow photic layer (about 10–15 m and not exceed 20–25 m in deep area). Most of the organic matter is synthesized by the phytoplankton during photosynthetic processes in a relatively narrow surface water layer of 0–10 m so-called particle production zone. The main biogeochemical transformation of the SPM composition took place within the narrow zone. POC content in the White Sea has mostly autochthonous (biogenic) genesis.

The SPM is a mixture of river lithogenic particles and marine biogenic particles. The proper marine SPM was found only in the deep part of the sea far from the sources of river runoff. The SPM grain-size composition and major constituents in the White Sea has been formed under influence of two main sources – lithogenic and biogenic – which are in complicated spatial and temporal interactions.

The spatial and temporal variations in SPM concentration in the photic layer of the White Sea were caused directly or indirectly by river runoff and, first of all, by the Severnaya Dvina River. Interannual variations in the SPM concentration based

on our multi-annual calculations for the White Sea were quite low; hence, they were statistically insignificant.

The vertical stratification (pycnocline which is confined by the halo- and thermocline) was the main factor that controlled the distribution of SPM in water column. We revealed three-layer vertical SPM distribution, so-called vertical zonality [1]: (1) the surface-mixed and photic layer, (2) the clear intermediate water layer, and (3) bottom nepheloid layer usually registered in the most of the near-bottom layer of the sea.

The most common grain-size type of the SPM was silty–pelitic polydispersity. The SPM was predominantly pelitic in June (after spring flood). In the stratified water column, the content of pelitic fractions changed little. This is so-called basic particles dispersion background of seawater. These fine particles reached the sea bottom just in a transformed form, i.e., captured by fecal pellets and aggregates of "marine snow," which form the vertical fluxes of dispersed sedimentary matter. These particles were studied with the help of other methods, and the results were presented in chapter [64]. Formation of the bottom sediments composition does not finish when SPM is deposited on the sea floor. The former SPM usually form a thin fluffy layer (about 0.5–1 cm) – a transition layer between two types of sedimentary bodies: a dispersed particulate matter (SPM) and consolidated particulate matter (bottom sediment). Fluffy layer consists mostly of organic and mineral aggregates; it lies over the relatively dense uppermost sediment layer saturated with water (till 90%) [22]. In this layer, the basic processes of SPM transformation into sediment occur, which later undergoes early diagenesis processes as well as bioturbation, resuspension, redeposition, etc.

Recent sedimentation processes in the White Sea are similar to that in the Arctic shelf seas subjected to a considerable impact of river runoff like the Kara and Laptev seas. However, the White Sea has some features which make this basin unique and perspective for further researches under the conditions of changing Arctic ecosystem.

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