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MARINE GEOLOGY

Results of Multidisciplinary Oceanographic Studies in the White Sea in June 2000

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Abstract—Multidisciplinary oceanographic studies of the White Sea were carried out in the regions of the Gorlo, of the Basin, and of Kandalaksha Bay including the estuaries of the Niva, Kolvitsa, and Knyazhaya rivers. The hydrographic survey revealed long-living stepwise structures and inversions in the vertical profiles of temperature and salinity formed due to the tidal mixing of saline and cold Barents Sea waters and warmer White Sea waters in the Gorlo area. The biological studies revealed the principal features of the distribution, abundance, and species composition of phyto- and zooplankton in all the areas studied. They showed the tolerance of the principal zooplankton species to desalination in the estuaries. The studies of the suspended matter in the estuaries clearly demonstrated physical and chemical transformations of the matter supplied by the rivers. The data on the vertical particle flux in the deep-water part of Kandalaksha Bay showed the difference between the subsurface layer and the near-bottom layer, which could result from the sinking of the products of the spring phytoplankton bloom and from the supply of the suspended terrigenous matter from the nepheloid layer formed by the tidal currents.

INTRODUCTION

Multidisciplinary oceanographic studies of the White Sea represent an important task at the present-day stage of the development of marine sciences. This inland sea of Russia is the most reachable for the studies; nevertheless, it is almost unknown from the systematic point of view. Due to the multiyear efforts of the scientists of Moscow State University (MSU) and the Zoological Institute, Russian Academy of Sciences, implementing both in marine expeditions and at the *Pertzov* and *Kartesh* White Sea biological stations [1, 13–25, 31, 33–35], as well as to the research performed by the All-Union and Polar institutes for marine fishery and oceanography [7, 28], the information on the hydrological parameters and the biological structure of the sea is the most abundant. Also available are the results of the geological studies performed by the scientists from All-Union Geological Institute and from the Laboratory for Shelf Studies of the Shirshov Institute of Oceanology, Russian Academy of Sciences (IORAS), aimed at the examination of the geological structure of the seafloor and its sedimentary cover [11, 12]. Along with this, one can state a significant deficit in the knowledge on the interrelations between the hydrophysical, biological, and geochemical processes in the White Sea and their role in the formation of the sediment fluxes toward the floor; on the riverine discharge of the sedimentary matter, its substantial and chemical composition, and the transformation of the matter supplied by the rivers; and on the hydrophysical, biological, and geochemical processes in the zone of mixing between the riverine and marine waters.

At the end of the 1990s, the Russian scientific community developed a series of national and international projects concerning system studies of the White Sea (INTAS 94-391, INTAS 96-1359, INTAS 97-1881, ICA2-CT-2000–10053, White Sea System-2000, and others). This paper presents the results of the studies implemented within the framework of the INTAS 97-1881 project from June 15 to 24, 2000, in the White Sea from aboard the R/V *Kartesh* by the IORAS together with the Geographical and Biological Faculties of MSU and Plymouth University (UK).

The objective of the project was a multidisciplinary study of the mesoscale hydrophysical, biogeochemical, and biological processes in the region of the Gorlo, in the deep-water part of the White Sea and in the zone of the marginal filter, and in the estuaries of the minor rivers flowing into Kandalaksha Bay. On the basis of the hydrophysical, biological, and sedimentation properties, we studied the mesoscale and fine structure of the water masses, the interaction between the deep-water and shallow-water areas, the vertical matter fluxes in these regions, the substantial and chemical composition

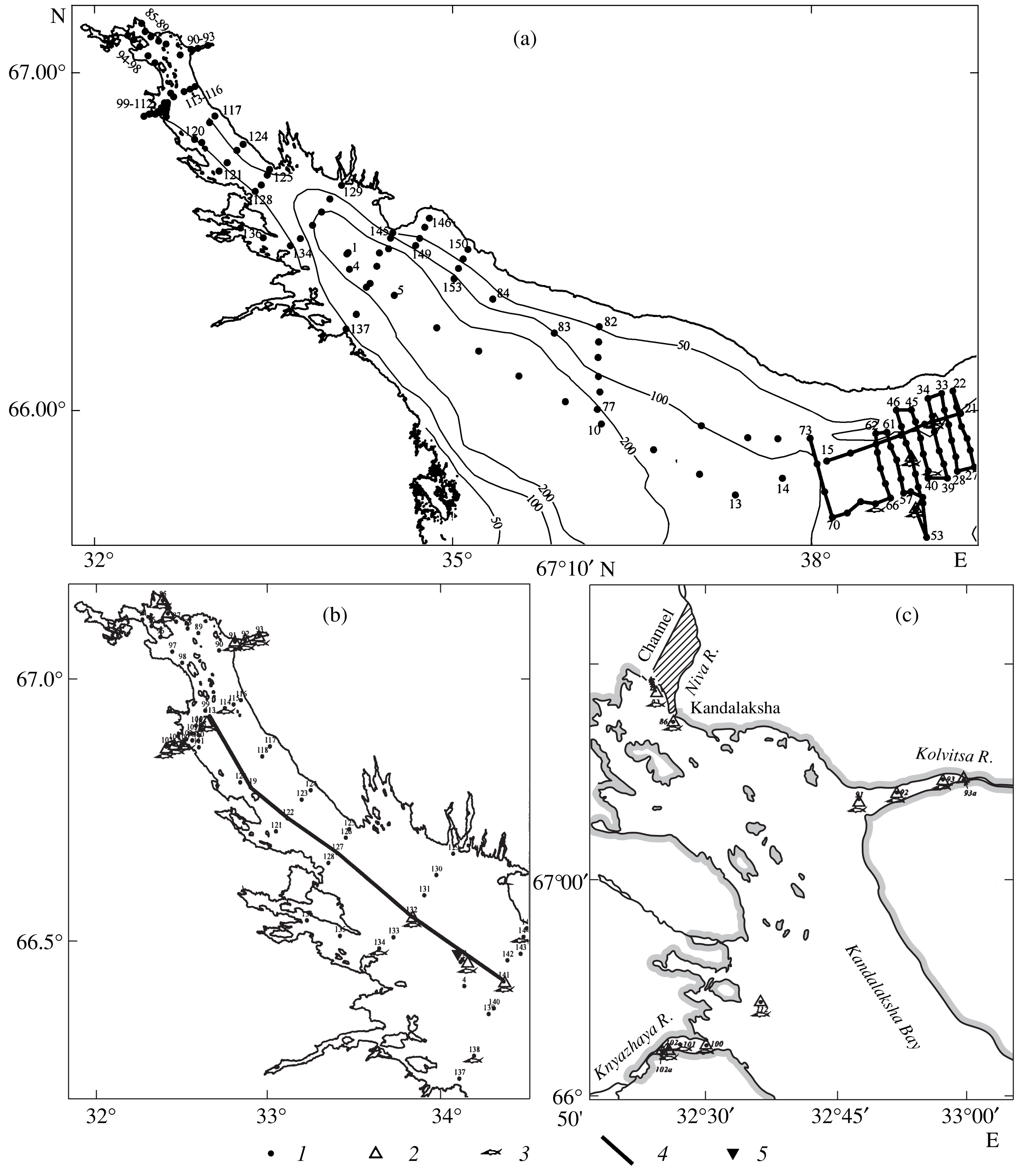

Fig. 1. Schematic of the station location. (a) Northwestern part of the White Sea; (b) location of the cross section along Kandalaksha Bay; and (c) near-mouth regions. (*1*) CTD probings; (*2*) water suspension sampling; (*3*) plankton net hauls; (*4*) cross section location; and (*5*) location of the station with sediment traps.

of the matter, and the processes of interaction between the riverine and marine waters in the estuaries of the minor rivers flowing into Kandalaksha Bay. The studies were implemented through the measurements of temperature, salinity, current velocity and direction, hydrochemical parameters, composition and distribution of phyto- and zooplankton, and the degree of transformation of the sedimentary matter delivered by the rivers. We examined the factors determining the features of the distribution and mutual interaction between different components of phyto- and zooplankton and estimated the contribution of biota to the production of biomass and to the sedimentation process. The studies were also aimed at assessment of the upper layer of the bottom sediments.

MATERIALS AND METHODS

The studies were performed in the northern part of the White Sea within three principal regions: (1) west of the Gorlo of the White Sea, (2) in the deep-water part of Kandalaksha Bay and in the basin off the Terskii Coast, and (3) in the estuaries of three minor rivers (the Niva, Kolvitsa, and Knyazhaya rivers) flowing into Kandalaksha Bay (Fig.1). On the whole, 154 stations were observed including 153 stations with CTD probing with a SBE 19 probe (Sea-Bird Electronics). At 25 stations, in parallel with the hydrological observations, we determined dissolved oxygen concentrations and pH values in situ with the help of a HI.9142 portable oximeter (Hanna) and Ekotest-110 ionometer. In total, 150 determinations were implemented at characteristic levels with regard to the vertical distribution of the hydrological parameters. At 18 stations located in the estuaries of the minor rivers of Kandalaksha Bay, in addition to the standard hydrochemical determinations (O_2 and pH), we collected water samples with a 30-l plastic bottle sampler with their subsequent preservation in order to study the features of migration of chemical elements (Si, P, Sr, Ca, F, and B) in the zones of mixing between the reservoir and marine waters [27].

Temperature and salinity measurements were performed from a drifting vessel; in order to check the identification of the fine structure of the water masses, profiles were recorded at both the probe sinking and surfacing. Signal processing was implemented following the technique suggested by M.F. Frolov and G.I. Shapiro with corrections in the readings of the pressure gauge; this allowed us to improve the vertical resolution of the temperature and salinity profiles from 1 to 0.4 m.

At anchor stations, we measured the current velocities and directions with a VALEPORT impeller with remote recording of the readings. In Kolvitsa Inlet, a half-day-long station with current measurements at 8 levels was observed.

The suspended matter samples were collected from the plastic water bottle samplers from various levels. About 150 samples were obtained by filtering through nuclear screens 47 mm in diameter with a pore size of 0.45 μm; about 75 samples were obtained by filtering through GF/F glass fiber screens 47 mm in diameter. In addition, 50 samples of filtrate were taken for determination of heavy metal concentrations.

Phytoplankton samples were collected from the bottle samplers from the levels where suspended matter samples were also taken. The samples were preserved in a 0.1% formalin solution. On the whole, 59 samples at 13 stations were collected. The processing of nonconcentrated samples (50 ml in volume) and the counting of mass forms of phytoplankton <20 μm in size were performed in a Fuchs–Rosenthal chamber over two weeks after their acquisition. Then, the samples were fixed in a 1% formalin solution for subsequent concentrating and counting of large (>20 μm) and low-abundant forms.

The zooplankton samples were collected with a Juday net with an opening of 37 cm and a gauze filtering cone with a mesh size of 180 μm by layer-by-layer vertical hauls in the water column from the surface to the bottom. The sampling levels were chosen with regard to the data on the vertical water structure acquired in the course of the hydrophysical probing. The samples were preserved in a 4% formalin solution. In total, 74 zooplankton samples at 22 stations were collected.

In order to study the vertical fluxes of the sedimentary matter in the deep-water part of Kandalaksha Bay at a point with a sea depth of 320 m, we installed a mooring station supplied with minor sediment traps. The exposure equaled to 7.83 days. The samples were fixed in a 2% formalin solution.

The samples of the bottom sediments (upper layer of the sediments 0–1 cm) were collected with a grab sampler in the river estuaries and in the central part of Kandalaksha Bay. The sediments were described, then dried at a temperature of 60°C and packed for the subsequent processing at the land laboratory.

RESULTS

Hydrophysical Studies

The hydrophysical studies off the Terskii Coast, in the deep-water part of the Basin, and in Kandalaksha Bay of the White Sea showed a wide development of stepwise and inverse structures in the vertical distributions of temperature and salinity. At a significant part of the stations, different numbers of steps (from one to five) 3–20 m thick were observed in the profiles of a single or both characteristics mentioned (Figs. 2a–2d). Another feature consists of the breaks in the vertical distribution plots recorded at a series of stations. The most complicated distribution of structural combinations was observed in a test area in the Gorlo region, which represents the principal area of their formation. Here, we recognized the following types of vertical distribution: (1) uniform down to the bottom deep-water layer covered by warmer and desalinated surface waters, (2) distributions with monotonic changes in the characteristics, (3) two- and three-step structures, and (4) structures with a temperature inversion. This kind of diversity is formed as a result of intensive tidal mixing and complicated interlayering between the transformed saline and cold waters of the Barents Sea penetrating from the north and the less dense desalinated warmer waters of the White Sea supplied from the south.

In the open part of the sea, in the intermediate layer 20–90 m, thick stepwise structures are observed (from one to three structures at each of the stations) with a horizontal extension up to 400 km (Fig. 3d). They are separated by water layers with enhanced vertical gradients of both temperature and salinity. The two thickest layers (hatched in Fig. 3d) have dome-shaped outlines corresponding to the principal cyclonic gyre in the basin. The temperature distribution observed in the western part of the basin indicates the possibility of sinking (cascading) of the mixed waters over the slope from depths of 80–100 to 180–200 m. Although additional studies are required to recover the true mechanism of the cascading, one can expect that it has an advective–gravitational origin, similar to that of the process of the slipping down of the dense waters over the northwestern shelf of Europe [32]. In the 0- to 20-m subsurface layer, we often observed less stable interlayers of mixed waters 3–5 m thick, which are best manifested in salinity profiles (Fig. 2d). The depths of the upper and lower boundaries of the mixed layers are irregular. This is caused, first, by the variability of the process of the formation of stepwise structures and, second, by the variability of the advection mechanism; probably, the presence of inertial oscillations also plays its part. As one can see from Fig. 3d, the stepwise structures are mainly formed in the shallow-water part of the Gorlo where homogeneous layers attain the shape of vertical columns forming sharp surface temperature fronts. This kind of fronts is not manifested in satellite images due to the screening effect of the warm surface waters. A similar phenomenon was observed in the Scotia Sea in the Antarctic [29]

We managed to resolve the mesoscale water structure due to the dense network of stations in a minor test area in the northern part of the Gorlo, where the intensity of the subsurface fronts reached 0.6°C per 10 km. From the fact that, in the direction from the basin toward the Gorlo region, the interlayers of the mixed intermediate waters continuously transfer to quasi-homogeneous volumes of the near-bottom waters, one can suggest that the protection mechanism of their formation is related to the turbulent mixing induced by strong tidal currents and bottom friction. This process, as well as the water advection from the Gorlo region to the deep-water part of the sea, proceeds most intensively during the spring tide periods, when the velocities of the tidal currents are two- to threefold greater than those during the neap tides; the horizontal displacements of the water masses over a tidal cycle are correspondingly greater. Therefore, the tidal "plunger" operates more efficiently providing the basin with recurrent portions of water.

The hydrological survey of Kandalaksha Bay showed a high degree of desalination of the entire water basin. The salinity of the subsurface layer gradually increased from 8‰ in the top part of the bay up to 23‰ at its seaward boundary. The vertical temperature structure in the deep-water part of the basin manifests no signs of a cold intermediate layer; this suggests a mild preceding winter in the White Sea (Figs. 3a, 3b). At a series of stations stepwise structures were observed, including those located in the near-bottom layer. This allows one to suppose that the stepwise features could be of a local origin; they might be generated by the tidal mixing over swells, banks, and steep slopes.

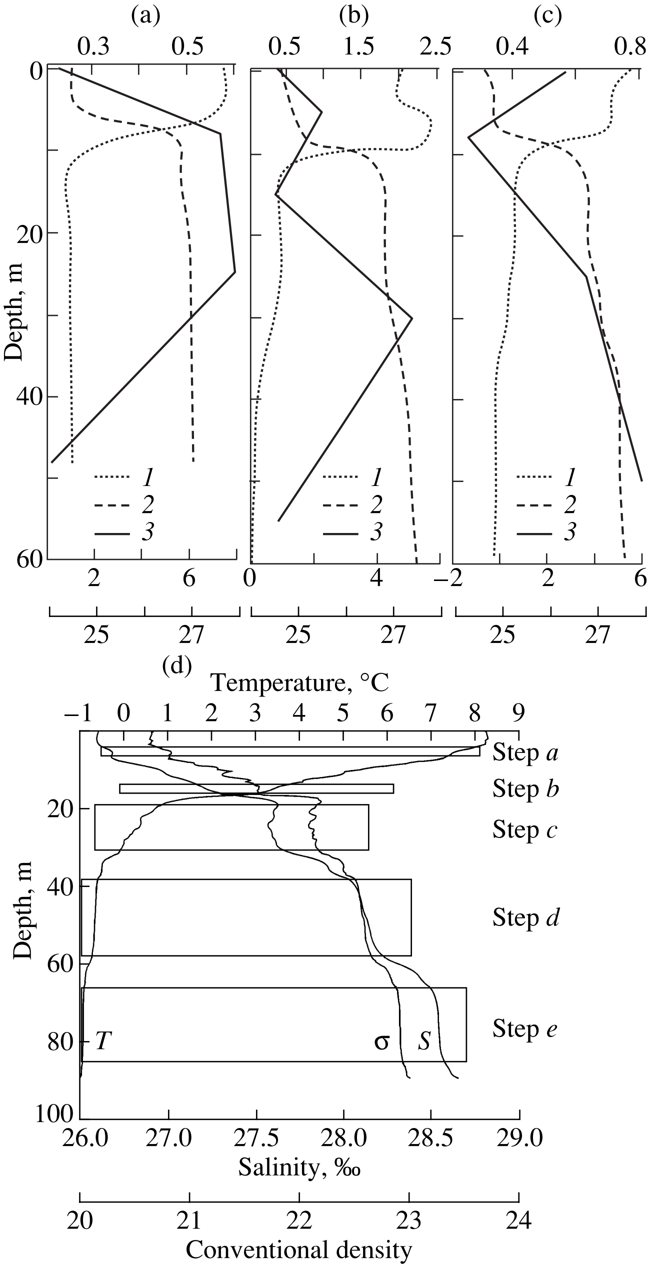

Fig. 2. Distributions of temperature (*T*, °C), salinity (*S*, ‰) and suspended matter concentrations (mg/l) at stations (a) 20, (b) 49, (c) 54 in the Gorlo region, and (d) fine structure profiles at station 14 in the deep-water part of the basin. (*1*) Temperature, (*2*) salinity, and (*3*) suspended matter concentration.

The observations in the estuaries of the Kolvitsa and Knyazhaya rivers showed strong two-layered circulations accompanied by the entrainment effects at the boundary between the currents. The velocities of the sink surface current in the top part of the estuary of the

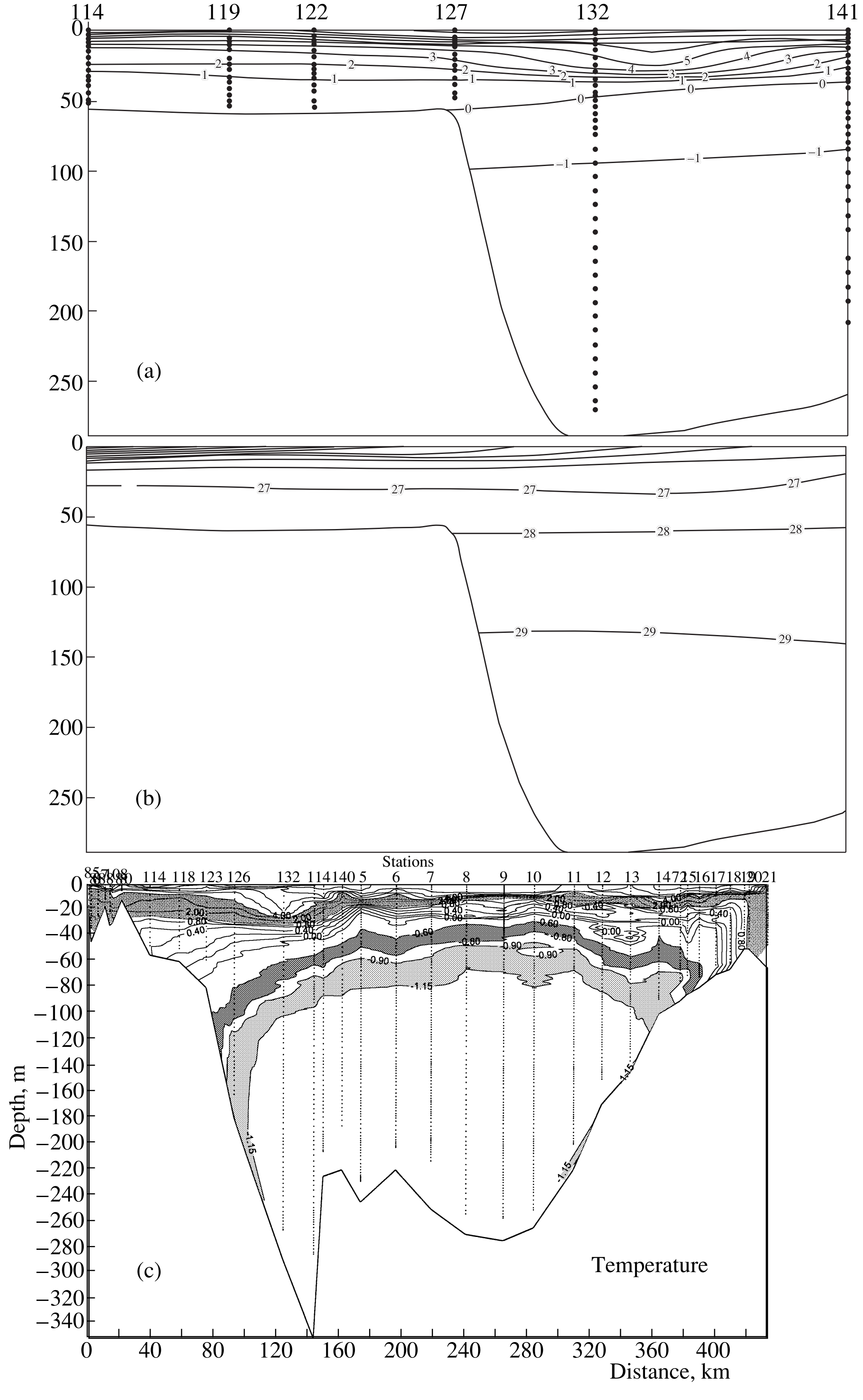

Fig. 3. Distributions of (a) temperature, *T*, °C, (b) salinity, *S*, ‰, in the axial section along Kandalaksha Bay, and (c) temperature distribution over the longitudinal profile Kandalaksha–Gorlo. Two of the three quasihomogeneous interlayers observed at the intermediate level and one of two in the subsurface layer are hatched.

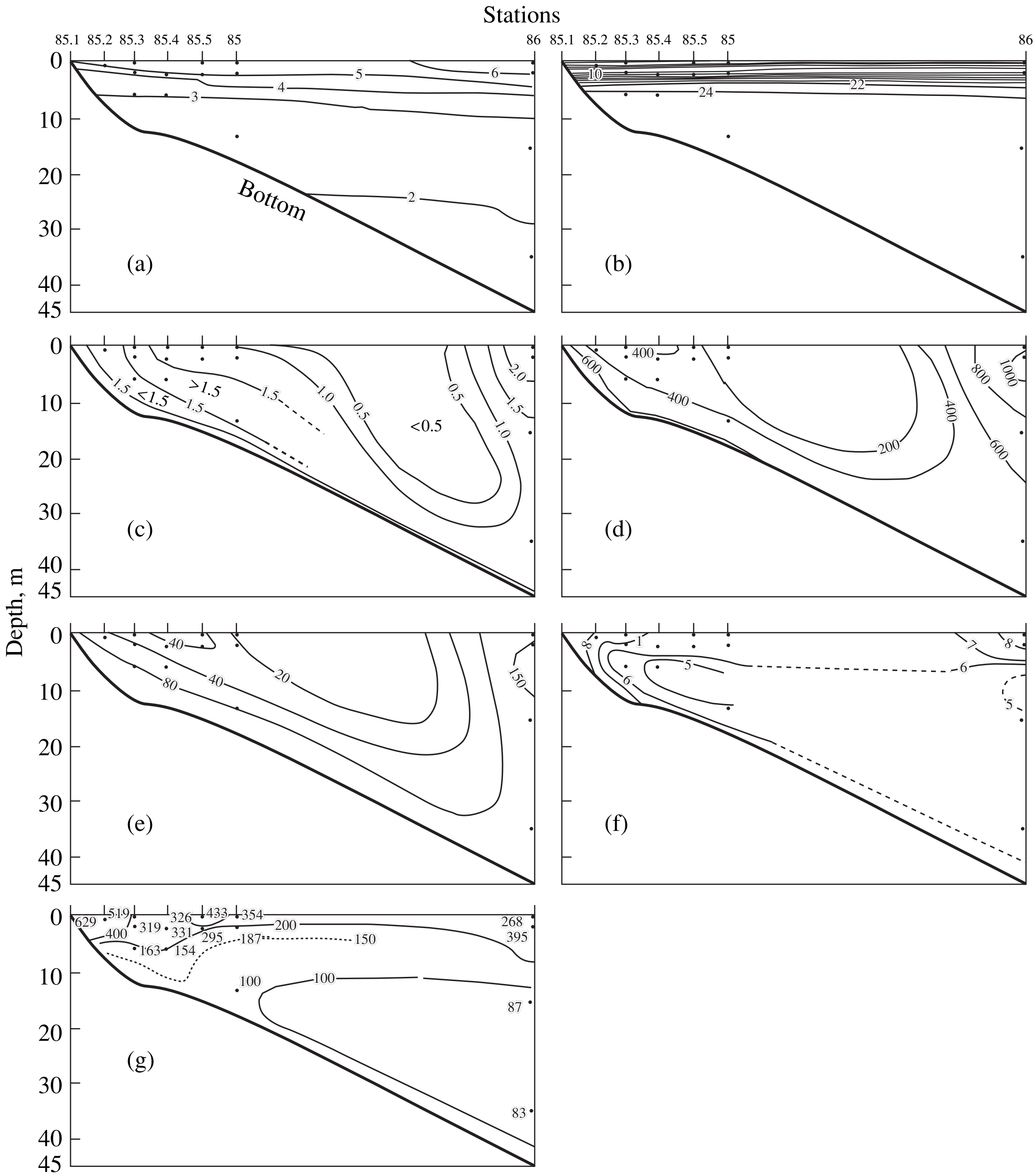

Fig. 4. Distributions of (a) temperature (*T*, °C), (b) salinity (*S*, ‰), concentrations of (c) suspended matter (mg/l), (d) Si (μg/l), and (e) Al (μg/l), (f) Si : Al ratio, and (g) C_{org} concentrations (μg/l) in the Niva River estuary.

Knyazhaya River reached 90 cm/s; at a depth of 4 m, the current was replaced by an oppositely directed one with a maximum velocity of 20 cm/s. At the exit from the estuary, a small-scale surface was performed; it showed that the desalinated waters spread in the form of a train rather than as a compact jet.

In the estuary of the Kolvitsa River, the thickness of the desalinated surface layer was 1.2 m and the velocity of the sink current at the surface reached 16 cm/s. Its replacement by a backward current occurred at a depth of 2.5 m. The hydrological structure in the Kolvitsa River estuary was three-layered. The warm and desalinated surface layer 2 m thick was underlain by a layer with temperature and salinity distributions similar to those in the swell region representing the zone of the influence of the compensational current arriving from the sea. At depths of 20–25 m, the pycnocline is located; deeper begins the water layer of the estuary basin with $T = -0.8$°C and $S = 28.2$‰. The above difference of the deep water temperature in situ from the freezing point suggests a more complicated process of its formation rather than a high degree of its transformation. This process seems to be more complicated than simple winter vertical convection with salination from ice generation.

Hydrochemical Studies

The studies performed in the estuaries of the minor rivers of the Kandalaksha Bay catchment (the Niva, Kolvitsa, and Knyazhaya rivers) allowed A.V. Savenko to recognize the nonconservative behavior of phosphates and silicon [27]. Both in the riverine waters and at the seaward boundary of the mixing zone, phosphate concentrations are low and comprise 0.006–0.010 and 0.003 mg P/l, respectively. Therefore, the removal of the main amounts of PO_4^{3-} occurs as early as in the zone of the riverine water domination. The maximum phosphate removal determined from the maximum deviations of the observed data from the conservative behavior trend is noted at a chloride concentration of 3.5 g/l. In contrast to phosphates, dissolved silicon is most intensively absorbed in the zone of the predominance of marine waters. The maximum removal of dissolved silicon observed at chloride concentrations of about 9 g/l depends directly on the silicon concentrations in the mouths of the Niva, Kolvitsa, and Knyazhaya rivers—1.0, 2.2, and 1.7 mg/l, respectively.

On the contrary, the behavior of strontium, potassium, fluorine, and boron in the estuaries of the rivers studied follows conservative mixing laws. Under a chloride concentration change from 0.02–0.06 to 15 g/l, a linear increase in the strontium and potassium concentrations takes place. At the transition from the riverine to marine waters, the value of the Sr : Ca weight ratio remains approximately the same, equal to 0.02–0.03, which suggests a similar ability of strontium and potassium to accumulate in the waters with an elevated mineralization.

With the growth of the chloride content, the fluorine and boron concentrations in the estuaries of the Niva, Kolvitsa, and Knyazhaya rivers also linearly increase. At the transition from the riverine to marine waters, the F : Cl and B : Cl ratios monotonically decrease; their changes are most significant at the initial stage of the mixing between the riverine and marine waters, and the ratios reach constant values at chloride concentrations greater than 3 g/l [27].

Biological Studies

The composition of both phyto- and zooplankton in the three regions studied—west of the Gorlo, in the central deep-water part of the sea, and in the estuary zone—was noticeably different. According to the data by T.N. Rat’kova, in terms of both biomass and abundance, phytoplankton was dominated by small flagellates; however, active bloom was noted only in the Gorlo region. The diatoms of this region were dominated by *Sceletonema costatum*, a mass form of the summer period typical of eutrophicated waters. Zooplankton was poor in terms of abundance (mean abundance value over the water column of 2000 ind./m^3). Juveniles of the mass Arctic copepod *Calanus glacialis* (nauplii and copepodites I–III) dominated its composition together with the Arctic–boreal species *Pseudocalanus minutus.*

In the central deep-water region we noted bloom of the flagellate alga *Phaeocystis* sp. Zooplankton was dominated by the species of the Arctic assemblage—copepods *C. glacialis* (represented by two generations), *Metridia longa*, *P. minutus*, and chaetognath *Sagitta elegans.* The vertical distribution of the zooplankton abundance was typical of the spring period with a clearly expressed maximum near the surface (>25000 ind./m^3 in the layer 0–10 m) and a sharp drop in the deeper layers (down to 40 ind./m^3 in the layer 200–300 m). A rather high biomass value and a distinct separation of different generations of *C. glacialis* over the water column were noted. In the surface layer 0–10 m, juveniles (nauplii and copepodites I–III) were abundant, while the individuals of the overwintered generation (copepodites V–VI) had already descended down to depths greater than 50 m.

In all of the three estuaries studied, we noted the bloom of the flagellate algae *Phaeocystis* sp., while diatoms were dominated by pennate forms. The composi-

Table 1. Percentage of freshwater, euryhaline, and marine species in the total abundance of zooplankton (ind./m^3) in the estuary of the Knyazhaya River, Kandalaksha Bay of the White Sea

Station no.	Station 102	Station 101		Station 100		
Date	June 21, 2000	June 21, 2000		June 21, 2000		
Sea depth, m	7	22		25		
Layer, m	0–6	0–6	6–20	0–3	3–10	10–22
Salinity	5.68–7.55	7.74–22.9	23.0–26.9	4.86	22.8	27.6
Total abundance, ind./m^3	26880	47460	18464	3992	13740	9363
Freshwater (%)	17.7	0.7	0.7	27.8	0	0
Euryhaline (%)	7.0	4.2	3.7	29.2	1.5	0.03
Marine (%)	75.3	95.0	95.0	43.0	98.5	99.97

Table 2. Percentage of freshwater, euryhaline, and marine species in the total abundance of zooplankton (ind./m^3) in the estuary of the Niva River, Kandalaksha Bay of the White Sea

Station no.	Station 85			Station 86		
Date	June 19, 2000			June 20, 2000		
Sea depth, m	18			45		
Layer, m	0–3	3–8	8–14	0–3	3–25	25–40
Salinity	6.65–21.0	>21.0	26.8	>1.23	2.0–27.0	27.0–27.2
Total abundance, ind./m^3	1893	28716	28438	11128	5508	4333
Freshwater (%)	18.1	0.007	0	8.3	2.1	0.03
Euryhaline (%)	4.6	1.04	0.03	16.9	4.1	2.7
Marine (%)	77.3	98.9	99.97	74.8	93.8	97.27

tion and distribution of zooplankton occurred to be rather diverse. At a series of stations in the estuaries of the Niva and Knyazhaya rivers (stations 85, 100; Tables 1, 2), in the desalinated surface layer 0–3 or 0–6 m at a salinity of 1.2–6.5‰, we observed both freshwater (*Bosmina coregoni, Sida crystallina, Linocalanus glimaldii*, Cyclopoida, Rotatoria) and euryhaline species resistant to strong desalination (*Podon leukarti, Evadne nordmanii, Acartia longiremis, A. bifilosa, Centropages hamatus*, and *Derjuginia tolli*). However, both in this layer and beneath it, common marine neritic species *Pseudocalanus minutus, Oithona similis, Metridia longa, Calanus glacialis, Sagitta elegans, Microsetella norvegica*, and others dominated in terms of both species number and abundance of planktonic organisms. Among the latter, *P. minutus* dominated (up to 63% of the total zooplankton abundance). The presence of freshwater species in the upper desalinated layer at these stations undoubtedly implied a significant influence of the freshwater runoff; meanwhile, the total zooplankton abundance in this layer was usually extremely low. In deeper layers, due to the sharp salinity increase up to 21–27‰, freshwater species were almost completely absent and only marine species were encountered. The abundance of zooplankton in these layers increased by a factor of 40–150 due to the occurrence of marine forms, which suggests an intensive inflow of marine waters in the lower layers reaching even the innermost parts of the estuaries (see Tables 1, 2). The general character of the distribution and composition of zooplankton was quite similar to that described by M.E. Vinogradov *et al.* [2] in the waters of the Yenisei River estuary, where they observed a distinct separation of the upper desalinated riverine layer from the lower marine layer with a relatively high salinity. The plankton of the brackish-water assemblage inhabiting the desalinated surface waters of the Yenisei estuary was also poor in abundance; in the deeper more saline waters, the plankton biomass was significantly higher due to the presence of marine species.

In addition, in the estuaries of the Niva and Knyazhaya rivers, we discovered one more type of zooplankton distribution. Thus, at stations 86, 101, and 102, in spite of the strong desalination of the surface layer, the maximum zooplankton abundance was observed precisely near the surface. In so doing, freshwater and euryhaline species in the surface layer were not abundant, while the abundance of marine species reached high values (see Tables 1, 2). The features of the vertical distribution of abundance were similar to those in the open part of Kandalaksha Bay with a maximum at the surface and subsequent decrease with depth. Most probably, in this kind of small estuary, the zooplankton distribution and its species composition are determined not only by the degree of the surface water desalination and the salinity gradient value in the upper layer but also by the direction and intensity of the dominating currents. Probably, a certain role belongs to the tidal currents as well. In the region of stations 86, 101, and 102, the influence of the marine water inflow during our studies seemed to be stronger than that of the freshwater runoff. The great number of marine forms at all of the stations and their high abundance even in the desalinated surface layer shows that the impact of marine waters on the biota of the estuaries of the minor rivers of Kandalaksha Bay is generally very significant. This also implies that a number of marine species are resistant to strong desalination and easily withstand a salinity drop down to 6–8‰.

The estuary of the Kolvitsa River, representing a bucket-shaped inlet with a maximum depth of 75 m and a swell at a depth of 20 m at its boundary with Kandalaksha Bay, is somewhat different from the two above-described estuaries in the zooplankton composition. Despite the significant desalination of the surface 8- to 10-m layer, at three stations performed in this estuary, no freshwater species were observed; brackish-water species composed from 11 to 81.3%, while the rest of the plankton was represented by marine forms (Table 3). At all of these three stations, the absolute abundance values of euryhaline species were very close ranging from 3125 to 4550 ind./m^3; however, due to the

Table 3. Percentage of freshwater, euryhaline, and marine species in the total abundance of zooplankton (ind./m^3) in the estuary of the Kolvitsa River, Kandalaksha Bay of the White Sea

Station no.	Station 93		Station 92			Station 91		
Date	June 21, 2000		June 20, 2000			June 20, 2000		
Sea depth, m	25		65			36		
Layer, m	0–8	8–22	0–10	10–28	26–55	0–10	10–25	25–34
Salinity	0.5–17.5	17.9–28.2	4.9–16.8	23.0–28.6	>28.6	15.9–19.9	20.0–27.8	>27.8
Total abundance, ind./m^3	28396	8864	10188	5526	1272	5349	4455	3842
Freshwater (%)	0	0	0	0	0	0	0	0
Euryhaline (%)	11.0	0.02	44.7	4.5	0.05	81.3	3.0	3.5
Marine (%)	89.0	99.98	55.3	95.5	99.95	18.7	97.0	96.5

changes in the percentage of marine species, their proportion in the plankton of the surface 0- to 10-m layer increased from the inner part of the estuary toward its periphery. With regard to the composition of marine species, age composition of their populations, and character of their vertical distribution, the Kolvitsa estuary was quite similar to Kandalaksha basin. At all of the stations in the estuary, the maximum zooplankton abundance was observed in the surface layer, gradually decreasing with depth.

On the whole, in all three estuaries, a very high zooplankton abundance was observed. In the estuaries of the Kolvitsa, Niva, and Knyazhaya rivers its value averaged over the entire water column ranged from 4180 to 16000, from 5490 to 22420, and from 11650 to 26950 ind./m^3, respectively. The maximum abundance was confined to the stations closest to the river mouths, while toward the outer parts of the estuaries it gradually decreased. From the three estuaries studied, the richest in terms of abundance was the Knyazhaya Inlet.

Geological Studies

The geological research included the studies of the suspended matter in the mixing zones of the minor rivers flowing into Kandalaksha Bay (the Niva, Kolvitsa, and Knyazhaya rivers) and over a longitudinal profile in the central part of the bay and of the studies of the sedimentary matter fluxes and bottom sediments in its deep-water part. In this part of the White Sea, especially in the estuaries of the minor rivers, neither suspended matter and its composition nor vertical particle fluxes has been studied to date; therefore, the data presented here are pioneering.

Figures 4–6 show the cross sections of distribution of temperature, salinity, and concentrations of suspended matter and selected chemical elements (Si, Al, and C_{org}) over profiles running from the mouth areas of the rivers of Kandalaksha Bay. The coldest water was observed in the estuary of the Niva River; here, the surface water temperature was 4.5–6°C. In the estuaries of the Kolvitsa and Knyazhaya rivers, the water is warmer; its temperature reaches 7–8°C. The gradients of the temperature changes with depth are not great, and the position of the jump layer is defined by the distribution of salinity. The salinity data allow one to realize the water structure in the estuaries and the character of the zone of mixing between the riverine and marine waters. For example, in the Niva estuary, the salinity change from <2 up to 24‰ occurs within a layer less than 5 m thick; the respective values for the Kolvitsa and Knyazhaya rivers are 10 and 12 m. These data suggest a high intensity of the fresh water supply. It is known that the strongest transformation of the riverine matter supplied the seas is confined to the salinity range from 2 to 10‰, which is favorable for the flocculation of the matter delivered by the rivers and for colloid coagulation [4, 8, 9, 31, 38]. This salinity range is observed in the upper part of the jump layer at small (less than 1.5 km) distances from the mouths.

The estuaries under consideration are characterized by extremely small concentrations of suspended matter (less than 1.5 mg/l) in the river parts of the mixing zones (see Figs. 4–6). The principal reason for this lies in the low suspended matter concentrations in the rivers flowing into the White Sea from Karelia and Kola Peninsula. Their runoffs are controlled by the Niva hydroelectric power station, Lake Kolvitsa, and the reservoir of Knyazhaya Inlet. These rivers, as well as all the others, are characterized by a reduction in the surface suspended matter concentration with distance from the mouth down to <0.5 mg/l. In the cross section off the Niva River, this regularity is broken by a fourfold concentration increase at the terminal station of the section (station 86). This seems to be caused by the riverine water runoff of the second channel of the Niva River (see Fig. 4b), which has a great length and catchment area and therefore supplies greater amounts of suspended matter. In the water column of all the rivers, an

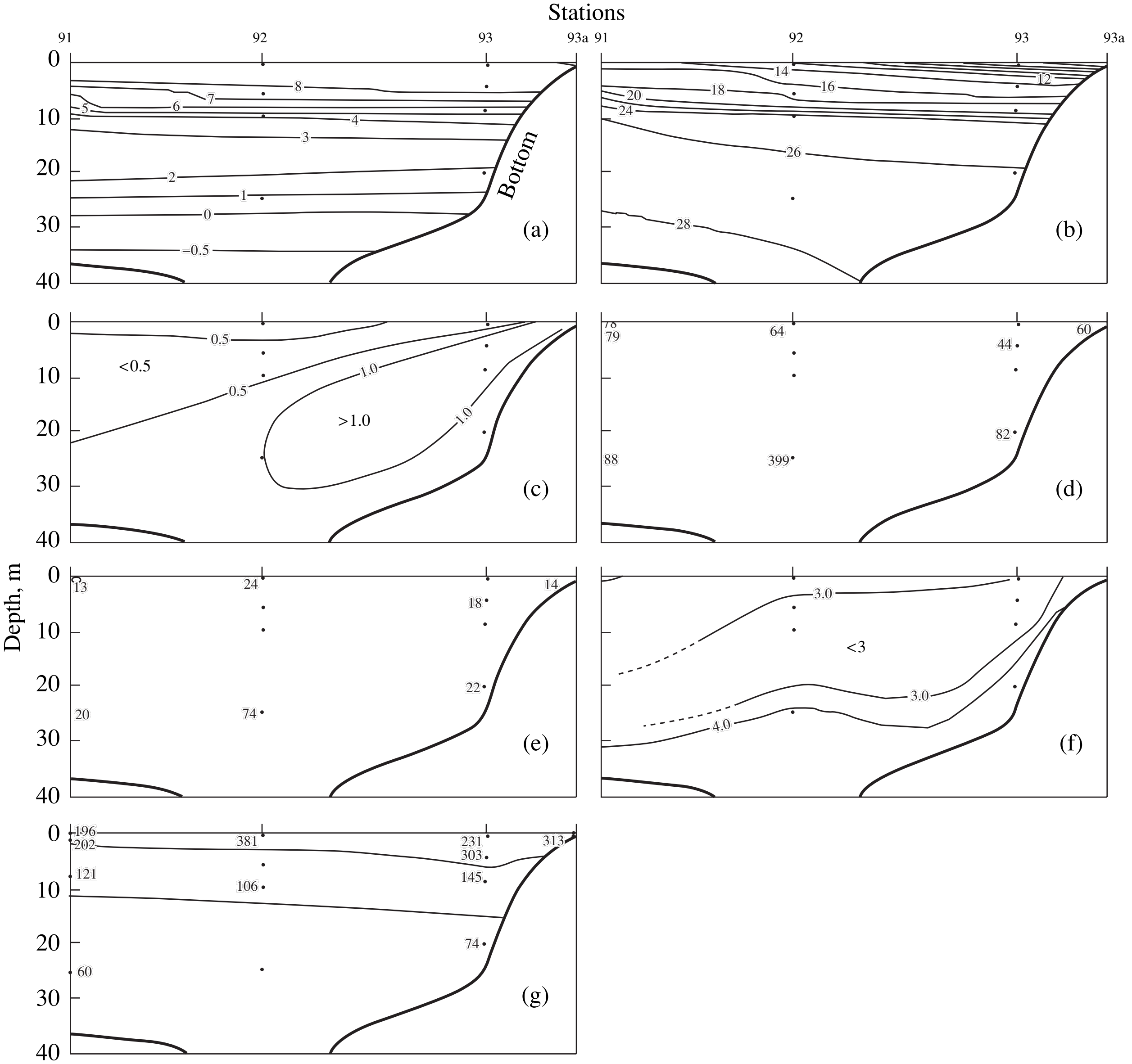

Fig. 5. Distributions of (a) temperature (*T*, °C), (b) salinity (*S*, ‰), concentrations of (c) suspended matter (mg/l), (d) Si (μg/l), and (e) Al (μg/l), (f) Si : Al ratio, and (g) C_{org} concentrations (μg/l) in the Kolvitza River estuary.

inclined layer with enhanced concentrations is observed extending seaward from the mouth areas. In this layer, suspended matter concentrations are higher than in the overlying and underlying waters; they are also greater than those in the freshwater parts of the estuaries. The concentration increase starts in the region of the salinity growth from 2‰; this is especially well manifested in the cross section from the mouth of the Knyazhaya River (Fig. 6c). Undoubtedly, the formation of this layer is related to the processes of transformation of the riverine matter at the river–sea barrier.

The data on the distribution of the chemical elements composing the bulk of the suspended matter (Si, Al, and C_{org}) also point to the transformation of the matter. The most representative data were acquired in the Niva estuary (Figs. 4d–4g). In Fig. 4d, the silicon distribution features high concentrations in the upper layers adjacent to the near-mouth parts of the estuaries of both river channels; this peak is caused by the presence of great amounts of diatoms (see above). The concentrations fall with distance from the mouths and with depth. The concentrations of aluminum, which serves as a marker of terrigenous and autigenous matter in estuaries [38], grow with depth (Fig. 4e). The values of the Si : Al ratio decrease with depth; its minimum values are confined to the layer of enhanced suspended matter concentrations (Fig. 4f). Beneath this layer, the values of Si : Al increase slightly; this is likely to be related to the resuspension of the bottom sediments resulting in the growth of the concentrations of both Si

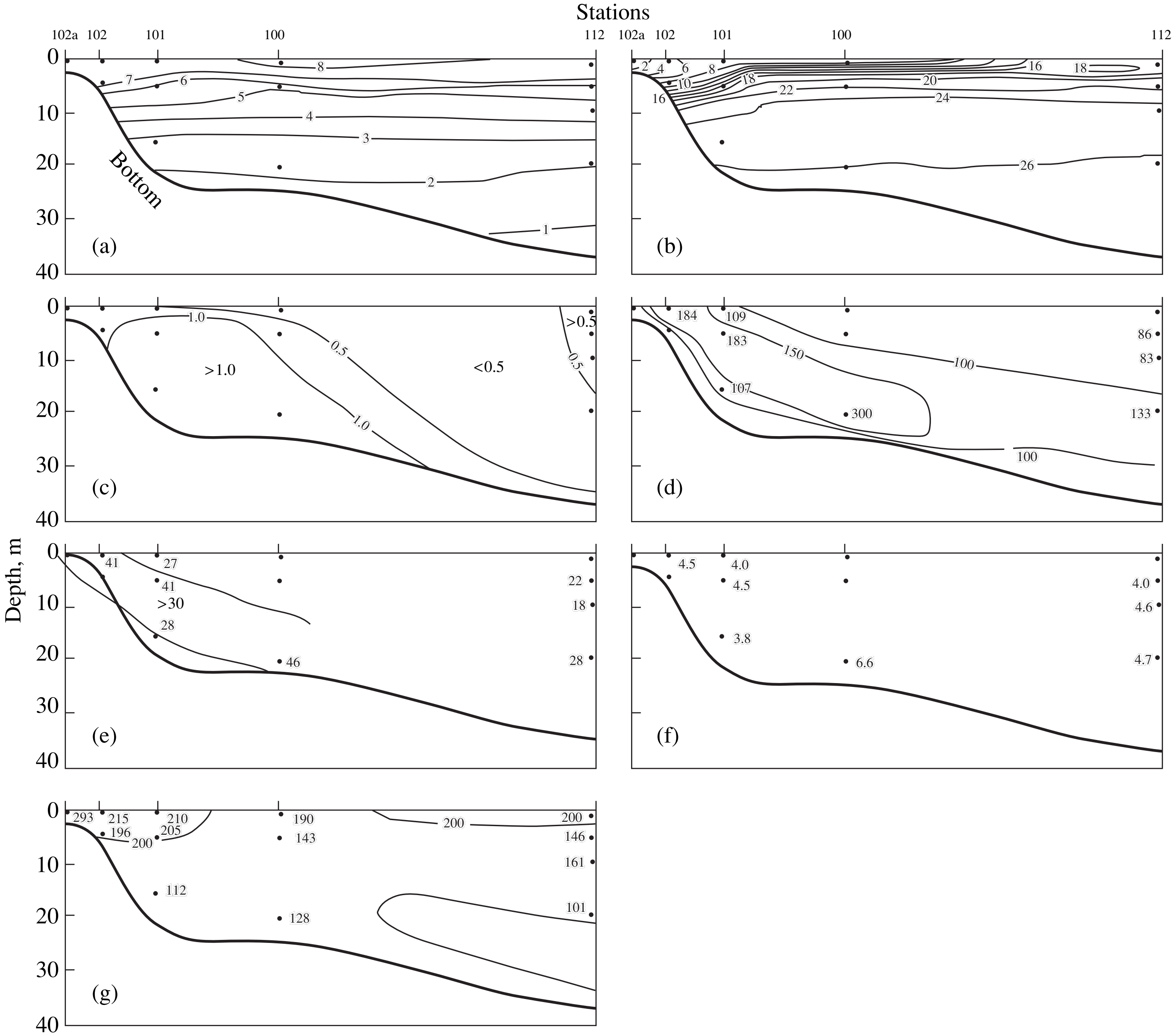

Fig. 6. Distributions of (a) temperature (T, °C), (b) salinity (S, ‰), concentrations of (c) suspended matter (mg/l), (d) Si (μg/l), (e) Al (μg/l), (f) Si : Al ratio, and (g) C_{org} concentrations (μg/l) in the Knyazhaya River estuary.

and Al. For the Kolvitsa estuary, the information on Si and Al is nominal (Figs. 5d–5f); nevertheless, judging from the values shown in the sections, one can also expect a slight growth in their concentrations. The regularities in the distribution of the chemical element concentrations are similar for all of the rivers. The values of the Si : Al ratio decrease in the layer of the enhanced suspended matter concentrations and increase in the near-bottom layer due to the turbidization of the bottom sediments.

In the surface layer (down to 5 m) of the near-mouth parts of all of the rivers, the concentrations of organic carbon are also high (Figs. 4g–6g); they fall with the distance from the mouth and with depth. Here, the high concentrations of C_{org} are caused by the development of diatoms and flagellates; in so doing, about one-third of C_{org} is provided by diatoms. The organic carbon concentrations in the near-mouth areas of other rivers are lower, though the features of its distribution are the same. Here, flagellates are mostly encountered.

Thus, the materials obtained show that, in the estuarine parts of the minor rivers of Kandalaksha Bay under consideration, one can clearly recognize the results of the physicochemical processes of transformation of the matter supplied by the rivers; this is manifested in the increase of the suspended matter concentrations with salinity changes due to coagulation of the colloids of the clay minerals delivered by the rivers and, partly, of

Table 4. Concentrations of suspended matter and suspended chemical elements at stations in the Gorlo region

Station no.	Coordinates		Sea depth, m	Level, m	Suspended matter concentration, mg/l	Chemical elements, µg/l							
	latitude, N	longitude, E				C_{org}	N	C : N	P	Si	Al	Si_{am}	Terrigenous matter
20	66°57.63′	39°02.78′	55	0	1.05 ± 0.45	164	25.4	7.5	1.9	54	9.2	25.4	107
				8	0.93 ± 0.27	216	32.0	7.9	4.7	223	25.8	144.0	300
				25	1.3 ± 0.30	102	13.4	8.9	2.9	293	63.4	99.4	739
				50	1.0 ± 0.20	96	12.0	9.3	2.5	253	56.6	80.7	660
49	65°52.50′	38°52.00′	65	0	1.23 ± 0.23	447	73.9	7.1	5.0	279	32.6	179.9	380
				5	2.11 ± 1.72	498	75.4	7.7	1.4	84	8.8	57.7	102
				15	0.68 ± 0.18	125	18.5	7.8	nd	136	34.1	31.7	397
				30	0.80 ± 0.10	76	10.6	8.3	2.2	212	49.9	59.4	582
				55	0.56 ± 0.15	77	8.8	10.2	1.2	123	22.5	54.3	263
54	65°42.43′	38°52.26′	60	0	1.3 ± 0.40	537	80.1	7.8	3.4	339	77.4	102.5	902
				8	2.0 ± 0.70	476	72.4	7.7	nd	nd	nd	nd	nd
				15	1.03 ± 0.30	195	28.2	8.1	nd	nd	nd	nd	nd
				25	1.35 ± 0.53	105	14.3	8.6	nd	nd	nd	nd	nd
				50	1.48 ± 0.44	169	19.4	10.1	nd	nd	nd	nd	nd

Table 5. Concentrations of the principal chemical elements in the materials of sediment traps and the vertical fluxes of the sediment-forming components

Chemical element	Concentrations, %		Sediment-forming components	Fluxes, mg m^{-2} day^{-1}	
	55 m	270 m		55 m	270 m
C_{org}	6.85	6.4	Organic matter	85.2	136.1
C_{carb}	1.14	0.68	$CaCO_3$	59.1	60.6
Si	30.06	29.1	SO_{2am}	337.7	469.1
Al	1.54	2.78	Terrigenous matter	111.6	344.3
Si : Al	19.5	10.5	Total	593.6	1010.1
C_{org}/P (at.)	111	83	Bulk flux	622	1063

the organic matter. This process is favored by the small concentrations of the terrigenous suspended matter driven by the rivers due to the controlled runoff of them.

The data on the distribution of temperature, salinity, and concentration of suspended matter and chemical elements in its composition over a cross section along Kandalaksha Bay are presented in Table 4 and in Fig. 7. They show that, in the seaward direction, the temperature in the surface layer decreases, while its salinity increases. A certain distortion of the relatively even distribution of these characteristics was observed at station 3, which was performed a week before the other stations of the section. At this station, we noted a growth in the concentrations of suspended matter, silicon, aluminum, and organic carbon, which can be related to the diatom bloom at the time of the observations. The suspended matter distribution is characterized by a growth of concentrations with depth, which may be caused by the sinking of the suspended matter formed during the spring phytoplankton bloom to the deeper layers and by the delivery of the suspended matter formed by the resuspension of the bottom sediments by tidal currents to the deep-water part of the bay. This is confirmed by the data on the sediment fluxes in the deep-water part of the bay obtained at station 2, located in the vicinity of station 3 (Table 5).

In the southern part of the Gorlo of the White Sea, suspended matter was collected at three stations. The sedimentary matter concentration at station 20 closest to the shore is characterized by a relatively even distri-

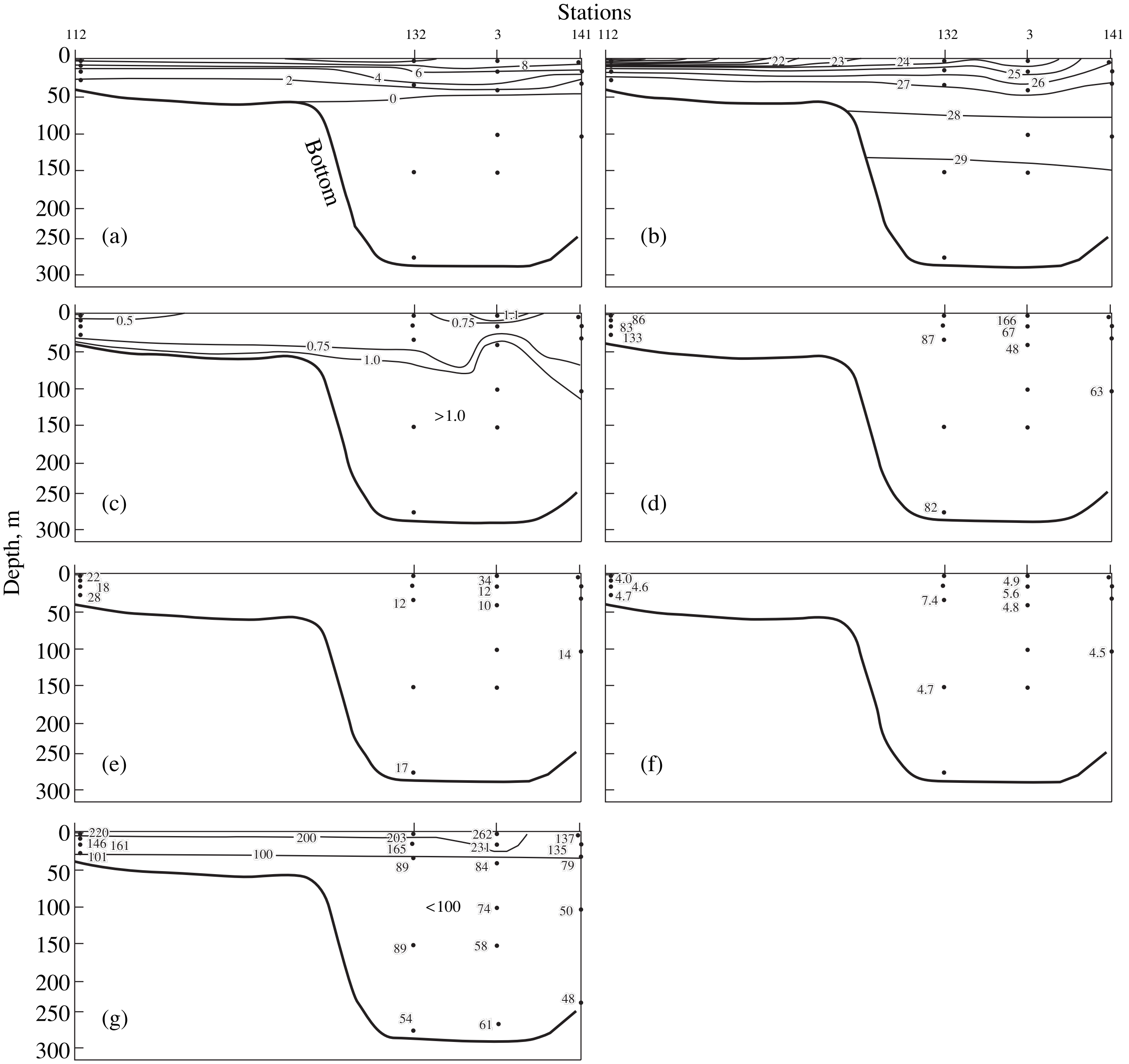

Fig. 7. Distributions of (a) temperature (T, °C), (b) salinity (S, ‰), concentrations of (c) suspended matter (mg/l), (d) Si (μg/l), (e) Al (μg/l), (f) Si : Al ratio, and (g) C_{org} concentrations (μg/l) in the axial cross section along Kandalaksha Bay.

bution curve (see Fig. 2a) free from significant deviations. At station 49 located in the central part of the Gorlo, we observed elevated concentrations in the upper mixed layer with a maximum in the jump layer; deeper, the concentrations decrease and reach their minimum near the bottom (see Fig. 2b). At station 54 (in the central part of the Gorlo) the suspended matter concentrations are maximum in the density jump layer, then they decrease, and grow again in the near-bottom layer (Fig. 2c). The distribution of chemical elements shows (Table 4) an enrichment of the upper mixed layer in organic carbon and silicon; judging from the values of the silicon-to-aluminum ratio, a significant part of the silicon is related to the diatom plankton. Beneath the jump layer, both the C_{org} concentrations and atomic C : N ratio increases at all of the stations; this implies a partial destruction of organic matter. Beneath the jump layer, the concentrations of Si at station 20 increase, while at station 49 they decrease; however, at both of the stations, the values of the Si : Al ratio fall with depth. This suggests that the principal silicon carriers are terrigenous alumosilicates. The increase with depth in the suspended matter concentration, especially in its terrigenous component, at stations 20 and 54 seems to point to a supply of the suspended matter entrained from the bottom and delivered by the Barents Sea water over the Gorlo swell.

An examination of the particle fluxes showed that the overall flux values are surprisingly high as compared to the data obtained in the Barents and Kara seas [37]. In Table 5 we present the concentrations of chemical elements and the fluxes of the sediment-forming components of the matter precipitating within the water column. Among the chemical elements, the highest concentrations belong to silicon; those of organic carbon, calcium carbonate, and aluminum are significantly lower; while the phosphorus concentrations are two orders of magnitude smaller. The Si : Al ratios show that the precipitating matter is dominated by the biogenic silica derived from the diatom plankton rather than by the silicate silica. In the lower layer (270 m), the concentrations of all the elements except for Al are lower than in the upper layer. The atomic C : P ratio at a depth of 55 m is close to the value characteristic of plankton [36], while in the deeper layers it decreases. Commonly, the values of this ratio increase with depth since phosphorus refers to the most labile components of organic matter. The increase of this ratio in the deep layer probably suggests an additional delivery of inorganic phosphorus to the suspended matter due to its sorption over the clayey matter and Fe hydroxides, as was reported for the sedimentary fluxes in the Norwegian Sea [9].

The fluxes of the sediment-forming components are calculated from the concentrations of chemical elements, which provide the values of concentrations of the sediment-forming components, and from the values of the total fluxes. The content of organic matter was determined by multiplying the C_{org} concentration by a factor of 2 [38]. The content of the diatom opal was estimated by the terrigenous matrix technique from the Si : Al value characteristic of the terrigenous matter. The suspended terrigenous matter consists mostly of clayey matter, and the ratio between the elements cited in the continental clays equals 3.05 [26]. Thus, the content of the terrigenous Si in the matter should be equal to the content of Al multiplied by 3.05, while the content of the siliceous (diatom) Si may be evaluated as total Si minus terrigenous Si. The content of the terrigenous matter is determined as the Al concentration multiplied by a factor of 11.65, which is obtained from the aluminum content in platform clays [26].

The data on the calculated fluxes of sediment-forming components show that the values for the 270-m level are higher than those for the 55-m level for almost all of the components. The carbonate flux values were close to each other and occurred to be the least; presumably, this was caused by the low amount of carbonate-concentrating organisms in the White Sea [1]. The fluxes of organic matter and amorphous silica equally increase (approximately 1.5-fold) which seems to imply one and the same group of planktonic carriers of these components. The elevated fluxes at the lowermost level are caused by the diatom bloom at the beginning of the exposure (see above). The increase in the terrigenous flux is especially great at the lower level (more than threefold), which results, similarly to the case of suspended matter, from the supply of the entrained matter of the bottom sediments to the basin.

In Table 6 we present the structure of the matter fluxes and the estimates of the percentages of their biogenic (organic matter, silica of the diatoms, and calcium carbonate) and terrigenous components. From the table, one can see that the compositions of the matter in the fluxes at both of the levels are close to one another. A twofold increase is noted only for the terrigenous matter at the lower level.

The upper layer of the bottom sediments (0–1 cm) collected in the estuarine zones of the Niva and Kolvitsa rivers is represented by oxidized silty–clayey ooze with a minor admixture of fine-grained sand. In the estuary of the Knyazhaya River, beneath the mainstream of the flow, fine-grained sand is encountered, while in the seaward part of the estuary, silty–clayey ooze is sampled. In the central part of Kandalaksha Bay, the sediments are clayey with an admixture of fine-grained sand covered with a fine oxidized layer less than 0.3 cm thick.

CONCLUSIONS

The presence of long-living stepwise and inversive structures in the vertical distributions of temperature and salinity were for the first time established in the deep-water part of the White Sea and in Kandalaksha Bay. These structures seem to be formed in the region of the Gorlo due to intensive tidal mixing and complicated interlayering between transformed cold saline waters of the Barents Sea penetrating from the north and desalinated warmer White Sea waters supplied from the south. Subsequently, these structures propagate into the White Sea over a distance of about 400 km. The intermittency of the layers with respect to

Table 6. Structure of the matter fluxes in the deep-water part of Kandalaksha Bay

Station no., depth	Level, m	OM, %	SiO_{2am}, %	$CaCO_3$, %	Terrigenous matter, %
3	55	13.7	53.3	9.5	22.2
320 m	270	12.8	40.9	5.7	39.8

the vertical is probably caused by the enhanced degree of turbulent mixing in shallow-water areas in the spring tide periods. In the estuaries of the minor rivers of Kandalaksha Bay, strong two-layered circulations were recognized: sink surface currents of desalinated waters with great velocities (up to 90 cm/s) overlay weaker countercurrents of the White Sea waters.

The hydrochemical studies in the estuaries of the minor rivers of Kandalaksha Bay showed that the changes in the concentrations of phosphates and silicon upon mixing between the riverine and marine waters proceeds in a nonconservative way, while the behavior of strontium, potassium, fluorine, and boron follows the laws of conservative mixing.

The biological studies showed that phytoplankton is everywhere dominated by flagellates both in terms of biomass and abundance (their bloom was noted everywhere). The diatom abundance was smaller, and in the near-mouth regions they were represented by pennate forms. In the Gorlo region, zooplankton, represented mostly by the juveniles of the Arctic copepod *Calanus glacialis*, was poor both in species and quantitative respects. In the central deep-water region, the zooplankton was dominated by the same species; however, its biomass was relatively high. In all of the estuaries, an extremely high zooplankton abundance was observed. The maximum abundance was observed at the stations closest to the river mouths; toward the outer parts of the estuaries it decreased. The composition and distribution of zooplankton in the near-mouth regions were rather diverse. The presence of freshwater species in the desalinated surface layer suggested a strong influence of the freshwater runoff. In the deeper layers, freshwater species completely disappeared due to the sharp salinity growth. The great amount of marine forms at all of the stations and their high abundance in the desalinated layer shows that the influence of marine waters on the biota is rather strong; meanwhile, many marine species demonstrate high resistance to significant desalination and easily withstand a salinity drop down to 6–8‰.

The study of the distribution and composition of suspended matter in the estuaries of the minor rivers of Kandalaksha Bay showed a clear manifestation of the physicochemical processes of transformation of the matter supplied by the rivers. They result in an increase in the concentrations of suspended matter and its components—organic and terrigenous matter (C_{org}, Al, and Si)—under salinity growth from 2 to 10‰. The suspended matter distribution over the median cross section of Kandalaksha Bay is characterized by an even distribution over the density jump layer and an increase in the concentrations with depth, which is likely to be related to the sinking of the suspended matter formed during the period of the spring phytoplankton bloom to deeper layers and to the delivery of the terrigenous suspended matter resuspended from the bottom sediments by the tidal currents to the deep-water part of the bay. The same reasons are responsible for the differences in the vertical matter fluxes at different levels and in the composition of the precipitating matter.

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