Hydrooptics and suspended matter of Arctic seas

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The basic features of the optical characteristics of Arctic sea water have been determined based on systematic study of the optical properties of water, distribution and composition of suspended matter, and flows of sedimentary matter in the sea water. Simultaneously the account was made of the physical, chemical, and biological fields of the Arctic.

Until now, the Arctic seas have been studied from the hydrooptics viewpoint only in very limited areas. Optical parameters were determined, as a rule, ignoring the data on content and composition of suspended matter, as well as physical and biological fields.

The first studies of the distribution of suspended matter in the Arctic go back to mid 1970's.[1] Then these studies continued with short breaks in the Laptev, Kara, and Barents Seas. However, the main instruments in those studies were membrane filters, which overestimated the content of suspended matter.[2,3] Only with the advent of nuclear filters in recent years it became possible to obtain reliable results on the distribution and composition of the suspended matter.[4–17]

Hydrooptical studies (especially, continuous vertical sounding) allow one to conduct real-time measurements and determination of the fine hydrooptical structure of the water depth. However, they do not provide information on the composition of suspended particles, which govern the optical properties of water.[7,18–22] Now it seems most worth studying the optical properties of the water depth simultaneously with the distribution and composition of suspended matter, as well as physical, chemical, and biological fields. Such studies can be conducted only from big vessels. The studies of that type became possible in 1991–1998 in ten research missions to Western Arctic.

Thanks to the use of a unified measurement technique and unified instrumentation, the comparative pattern was obtained for the optical properties, distribution of suspended matter, and other characteristics of sea water, from Laptev Sea in the East to Norwegian Sea in the West. Since rivers are the main sources of suspended matter, the vessel routs were drawn along the meridional river–ocean sections. This allowed us to evaluate the influence of the great Siberian rivers on the distribution of suspended matter and its physical properties. All these studies were conducted roughly in the same summer–fall season (from August to October). This also facilitated the comparison to be made among the data obtained.

In some missions, measurements at oceanographic stations were complemented with continuos determination of the optical properties of the surface water from aboard a moving vessel. These experiments were conducted with the instrumentation housed in a shaft at the central part of the vessel.[18] In some missions we had the opportunity of using the corresponding satellite data.[23]

Materials and methods

Most of the data on optical properties of water were obtained with a “DelfinB hydrooptical sonde.[7,18] The sonde was used for continuous vertical sounding of the extinction coefficient (ε_z) and temperature (T_z). It employed a two-channel optical arrangement with a photodetector and variable length of the measuring path. The extinction coefficient was measured in the range of its magnitude from 0.05 to 10 m^{-1} with the measurement error of 0.02 m^{-1}, the resolution was 0.003 m^{-1}. Temperature was measured accurate to 0.1°q , the submerge depth was 1 m, and the operating wavelength was 530 nm.

The information acquired during the measurements was transferred in real time through a cable to the onboard computer and was displayed on a monitor. Usually, the sounding with a hydrooptical sonde followed sounding performed with a hydrological Nail–Brown sonde and analysis of the fine hydrological structure of the water depth, the data on oxygen distribution, etc.

These two types of sounding allowed us to find the most interesting (“keyB) layer in every station. Then water from these layers was sampled using Rozette plastic bathymeter for enabling a thorough study of the suspended matter. A water sample usually had the volume of 10 to 30 liters.

The suspended matter was filtered out in vacuum with nuclear filter of 47 mm in diameter. The pore diameter of 0.45 μm in the filters used conforms the international standards. The amount of suspended matter was determined by weighing the filters after they achieved steady-state weight accurate to 0.05 mg.

During seven years of studies we succeeded to conduct vertical hydrooptical sounding at 250 stations (Fig. 1) and to take about 1900 samples of suspended matter at these same stations that enabled their thorough study.[7,9,14,17,18]

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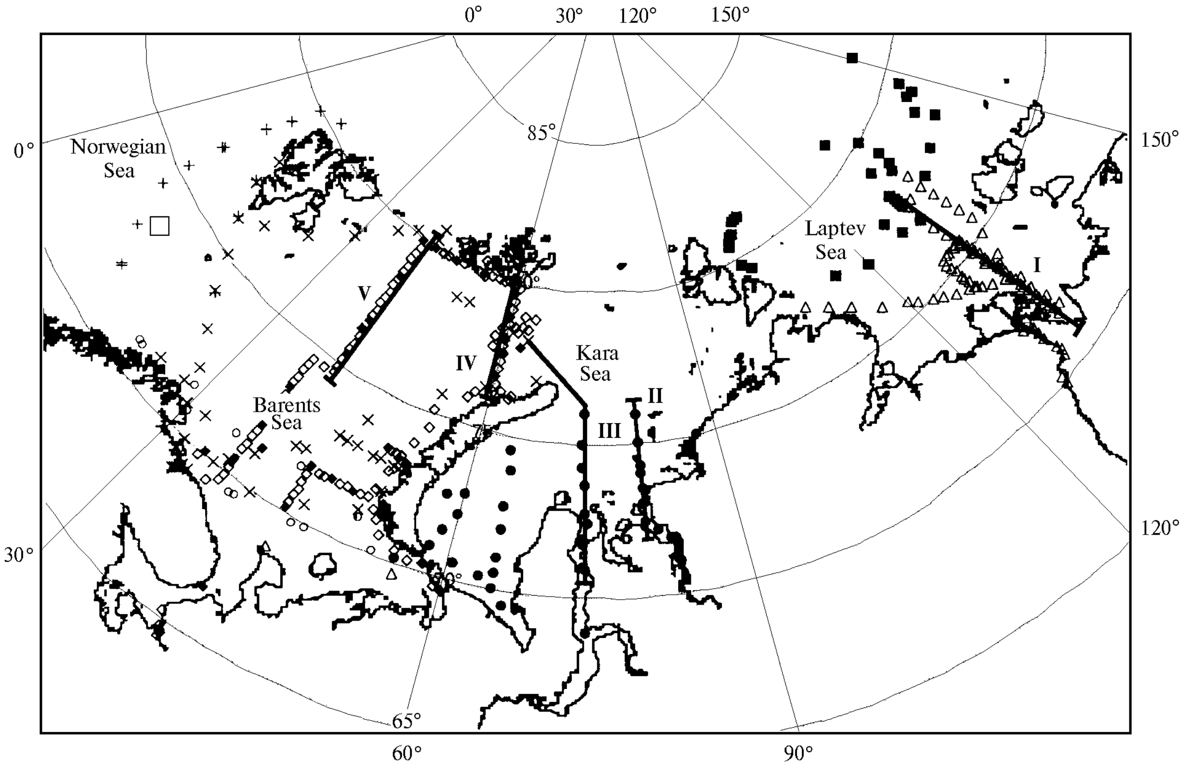

Fig. 1. Map of the sampling points in the Arctic seas: SPASIBA-91 mission (♦); 49th mission of *Dmitrii Mendeleev* RV, surface samples (Δ) and vertical sections (○); 9th mission of *Professor Logachev* RV (●); the mission ARK-XI/1 of *Polarstern* RV (×); 15th mission of *Professor Logachev* RV (■); 11th mission of *Akademik Sergei Vavilov* RV, only surface sampling (+) and vertical sections (◇); the place of wreck of *Komsomolets* atomic submarine, six-year studies aboard *Akademik Mstislav Keldysh* RV (□); latin digits mark the sections.

Besides, during six years the studies were conducted in the Norwegian Sea near Medvezhinskii Channel. This is the region where atomic submarine *Komsomolets* had wrecked.[24,25] These studies had not only research, but also applied significance: the forecast was needed on the spread of possible radioactive pollution in the suspended matter at the depth about 2 km in the case of leakage of radioactive materials.

In processing of the data we have found a dark correlation ($r = 0.90–0.97$) between the content of suspended matter C_{susp}, in mg/l, and the extinction coefficient ε, in m^{-1} (Fig. 2). The relation between them can be described by the equation of linear regression $C_{susp} = 0.81\varepsilon - 0.08$ for Laptev Sea and $1.66\varepsilon - 0.145$ for the Barents Sea.[7,14] In Barents Sea the correlation coefficient equals 0.90, that is, it is somewhat lower than in Laptev Sea. This corresponds to a wider variety of the suspended matter and the growing influence of its plankton as compared with that in Laptev Sea.

The studies of the composition of suspended matter included the study of its particle size distribution with a Cowlter counter[7] and a microscope, estimation of the contribution of mineral and biogenic particles, study of biogenic residuals, mineralogical X-ray analysis, study of the chemical and isotopic composition, detailed study of organic matter, pollutants, etc.[6,15,26–29]

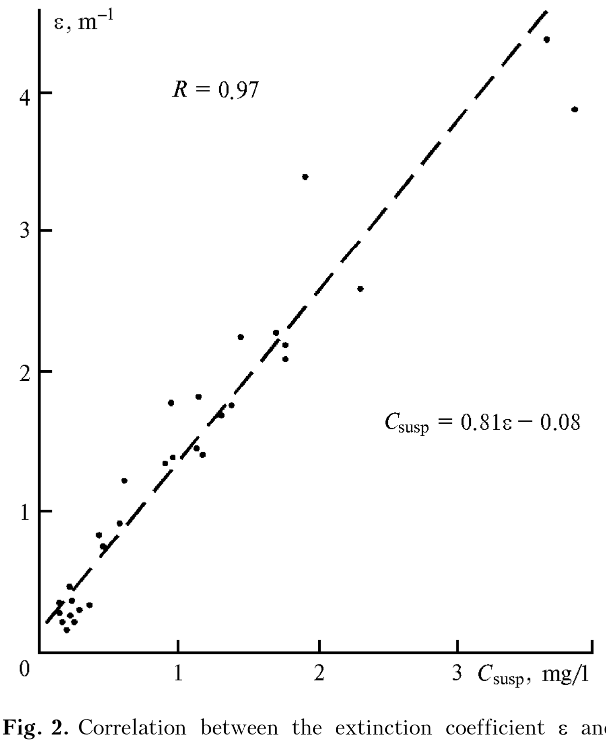

Fig. 2. Correlation between the extinction coefficient ε and amount of suspended matter C_{susp} in Laptev Sea in September 1991 (SPASIBA-91 mission) (Ref. 7).

Along with the data on physics, chemistry, and biology of the Arctic seas, this provided a unique ability of comparing the optical properties of water with the composition and amount of suspended matter and its properties. We also had an opportunity of using the results of earlier long-term studies of the surface water in Arctic with a Secchi disk (Fig. 3). In the Kara Sea the amount of incoming river water enriched with suspended matter is several times larger than in other Arctic seas. This is clearly seen from the 5-m transparency isoline, that shows the borders of the main area of influence of the fresh water from Ob, Yenisei, Pur, and Taz rivers. To the north and west from this area the water transparency by Secchi increases up to 15–20 m.

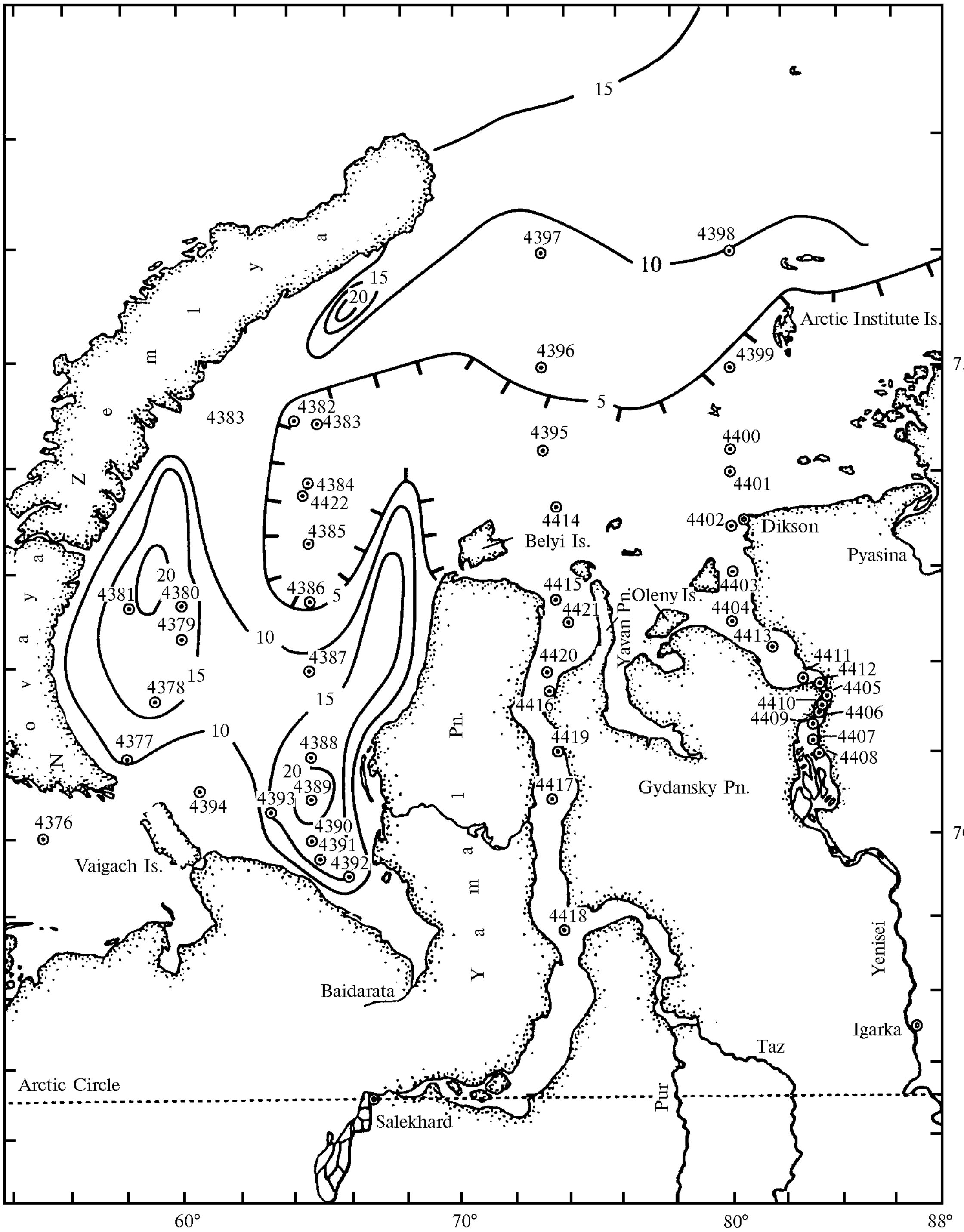

Fig. 3. Depth of visibility of a white disk in the Kara Sea (according to archived data and observations in the 49th mission of *Dmitrii Mendeleev* RV) (Ref. 18).

Discussion

The results obtained in Laptev, Kara, Barents, and Norwegian Seas, have been ordered for analysis to follow up the decreasing influence of the river water (from the east to the west), duration of ice cover, plankton productivity, and influence of the Atlantic water and climate.

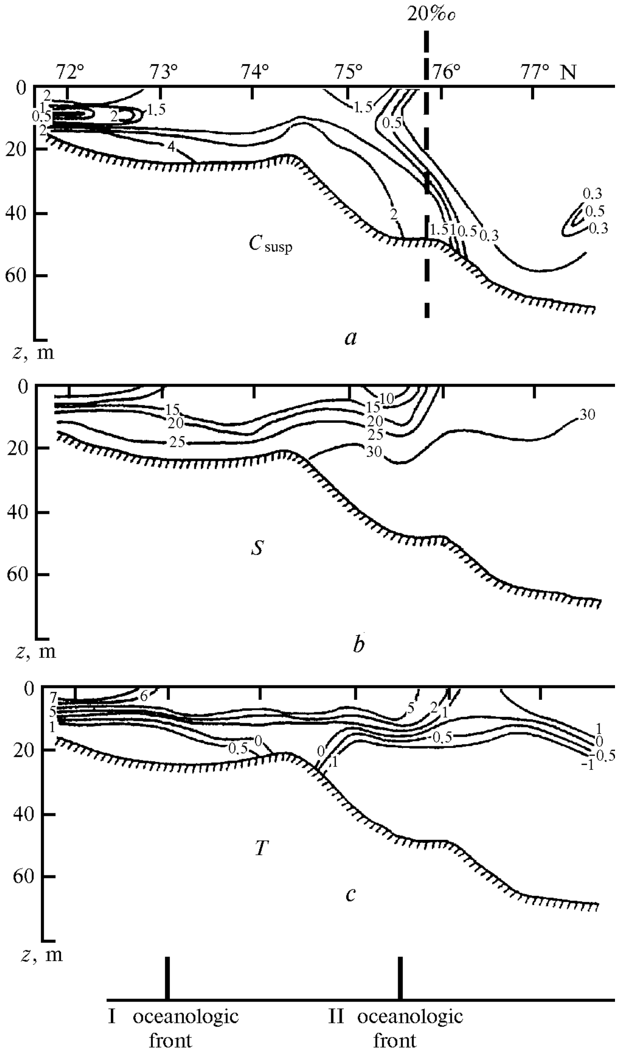

Fig. 4. The amount of suspended matter C_{susp} (*a*), water salinity *S* (*b*), and temperature *T* (*c*) in the section along 130°E meridian in Laptev Sea in late August – early September 1991 (Ref. 7).

Laptev Sea is distinguished by the most severe conditions there. Optics of water and suspended matter in Laptev Sea were studied aboard *Yakov Smirnitskii* RV in August–September 1991 (Ref. 7). Figure 4 shows how the amount of suspended matter changes in relation to temperature and salinity of water on the section coming to the north from the mouth of Lena River. The correlation between the amount of suspended matter (and, consequently, the extinction coefficient) and salinity is clearly seen from these data. Two oceanological fronts with very high gradients of the decrease in the amount of suspended matter are marked. They correspond to the isohalines of 10 and 20v . The mean content of suspended matter in water from Lena River was 20–40 mg/l (Ref. 30), and beyond the 20v isohaline it is less than 0.3 mg/l, that is, it decreases roughly by a factor of 100.

Similar pattern was observed in the surface water. In accordance with the distribution of salinity, the content of suspended matter here decreases by about 10 times with the increasing distance to the north from Lena River mouth. The most sharp decrease is also observed near the isohaline of 15–20v (Fig. 5).

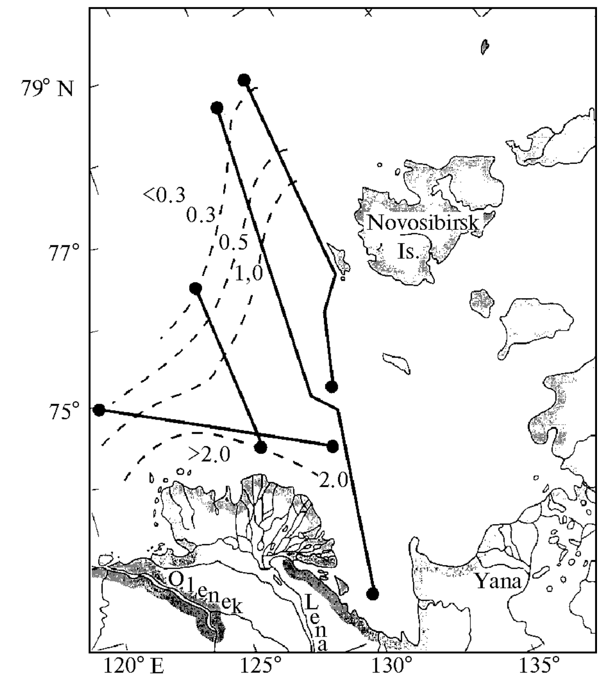

Fig. 5. Distribution of the suspended matter content (in mg/l) in the surface layer of Laptev Sea in late August – early September 1991: sections are shown by solid curves and content isolines are shown by dashed curves (Ref. 7).

Most detailed studies were conducted in Kara Sea in September – October 1993 during the 49th mission of *Dmitrii Mendeleev* RV.[6,9,26,28] Two meridional sections to the north from the mouth of Yenisei River (mean content of suspended matter in this river is 20–40 mg/l) and from estuary of Ob, Pur, and Taz rivers (mean content of suspended matter of 33 mg/l for Ob, 25 for Pur, and 20 mg/l for Taz) are most interesting (Fig. 6). Here, as in Laptev Sea, we can see a sharp decrease in the content of suspended matter as the salinity increases with a jump at the 20v isohaline. This decrease (by tens and hundreds times) corresponds to complex processes occurring in the zone of mixing of river and sea waters. In this zone, farther and farther away into the sea, the following processes sequentially give way to each other: gravitational sedimentation, physico-chemical processes in colloid systems (coagulation and flocculation, formation of Fe-sorbents and C-sorbents from solutions), and, finally, biological processes (development of phytoplankton from biogenic elements of the river water with the conversion of dissolved elements into biogenic suspended matter and the processes of biofiltration, that is, elimination of all types of suspended matter by organisms filtering zooplankton, mostly *Copepoda* crayfish).[31] As was found in this mission, the rate of biofiltration was very high – the total water volume of the estuaries was filtered for one to three days with removal of very fine-disperse particles of suspended matter and their transformation into coarse food lumps (pellets), which sediment fast to the bottom.[31–33]

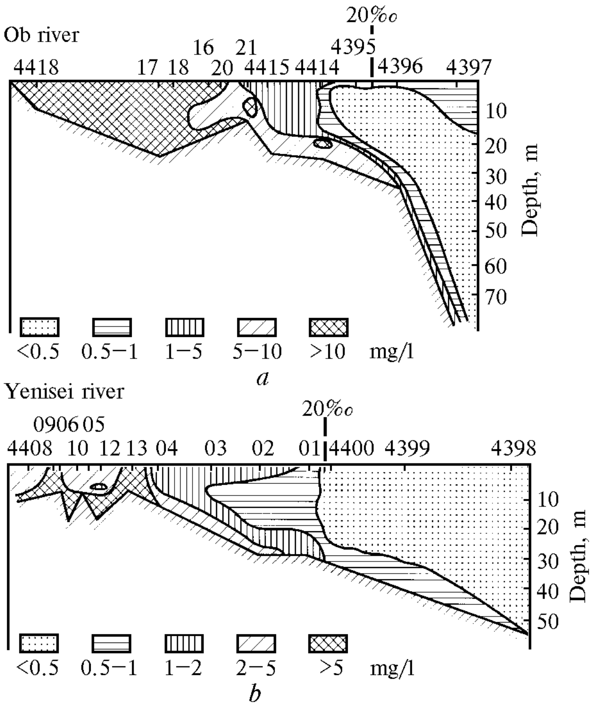

Fig. 6. Distribution of the suspended matter content along the river–sea sections in the mouth zones of rivers Ob (*a*) and Yenisei (*b*) in September 1993 (Ref. 9).

It was found that 90–93% of suspended matter of river water and 30–40% of dissolved elements deposit at the river–sea boundary. This phenomenon, the so-called “marginal filter,B takes place not only in the Arctic seas; it is a global phenomenon. Without going into details we can say that up to 20v isohaline the distribution of suspended matter and optical properties follow quite definite laws. Sedimentation exhibits here an avalanche behavior, and this area of the Global Ocean is called the zone of avalanche sedimentation of the first level.[34]

What are regularities in the distribution of the sedimentary matter and the extinction coefficient beyond the marginal filters?

Another one important regularity in the distribution of suspended matter and water turbidity was revealed from analysis of the surface water in St. Anna Channel (Fig. 7). The northern part of the region was covered with pack ice during the study. The content of suspended matter along the pack ice edge was 5 to 10 times higher than that in the regions spaced far from the ice edge. This phenomenon of marginal ice zone (MIZ) is attributed to the release of sediments (suspended matter) at ice thawing.[35,36]

According to our data, the mean content of suspended matter in the Arctic ice exceeds that in the sea water by 10 to 30 times and even more. Besides, cryosol material, thawing ice releases biogenic elements. This leads to local florescence of phytoplankton.

In summer the thawing-ice front gradually moves from south to north. The “Carpet releaseB of ice sediments (cryosols) occurs in combination with florescence of phytoplankton and development of the system of biofilters. The optical properties of water and content of suspended matter change correspondingly.

The third regularity, common for the Arctic, is associated with the vertical distribution of suspended matter beyond the marginal filters. As seen from Fig. 8, a sharp change in the extinction coefficient and the content of suspended matter is observed nearly always in the vertical sections above the jump layer. The phenomenon of “liquid bottomB occurs, in which a large amount of suspended matter is concentrated.

In the Arctic, under conditions of strongly distilled surface water, the density jump layer is especially pronounced.

One more regularity in the vertical distribution was revealed for the bottom layer of the Arctic water. When freezing, the sea water breaks down into the fresh-water part (ice) and brine; cold distillation of the sea water occurs. This results in formation of heavy cold water in the Arctic zones of intense ice formation. The heavy water moves near the bottom like heavy liquids. Together with the suspended matter, the heavy water flows down along the bottom along the general direction toward the continental slope, and then sinks downslope to large depths (phenomenon of cascading).[37]

We have managed to observe this phenomenon both in hydrooptical sounding of water and in sampling of suspended matter. It is clear that the flow of heavy water has the largest scale at ice freezing, that is, during the fall, as well as in winter in polynias at formation of in-water ice, as was found in the year-round observations. In some cases the bottom layer of turbid water (of nepheloid type) is observed in summer too. That is, this phenomenon is rather inertial in the Arctic. In contrast to other zones, where only local nepheloid layers arise near uplifts of the bottom and in shallows, the nepheloid layers in the Arctic achieve maximum scale in space and time.

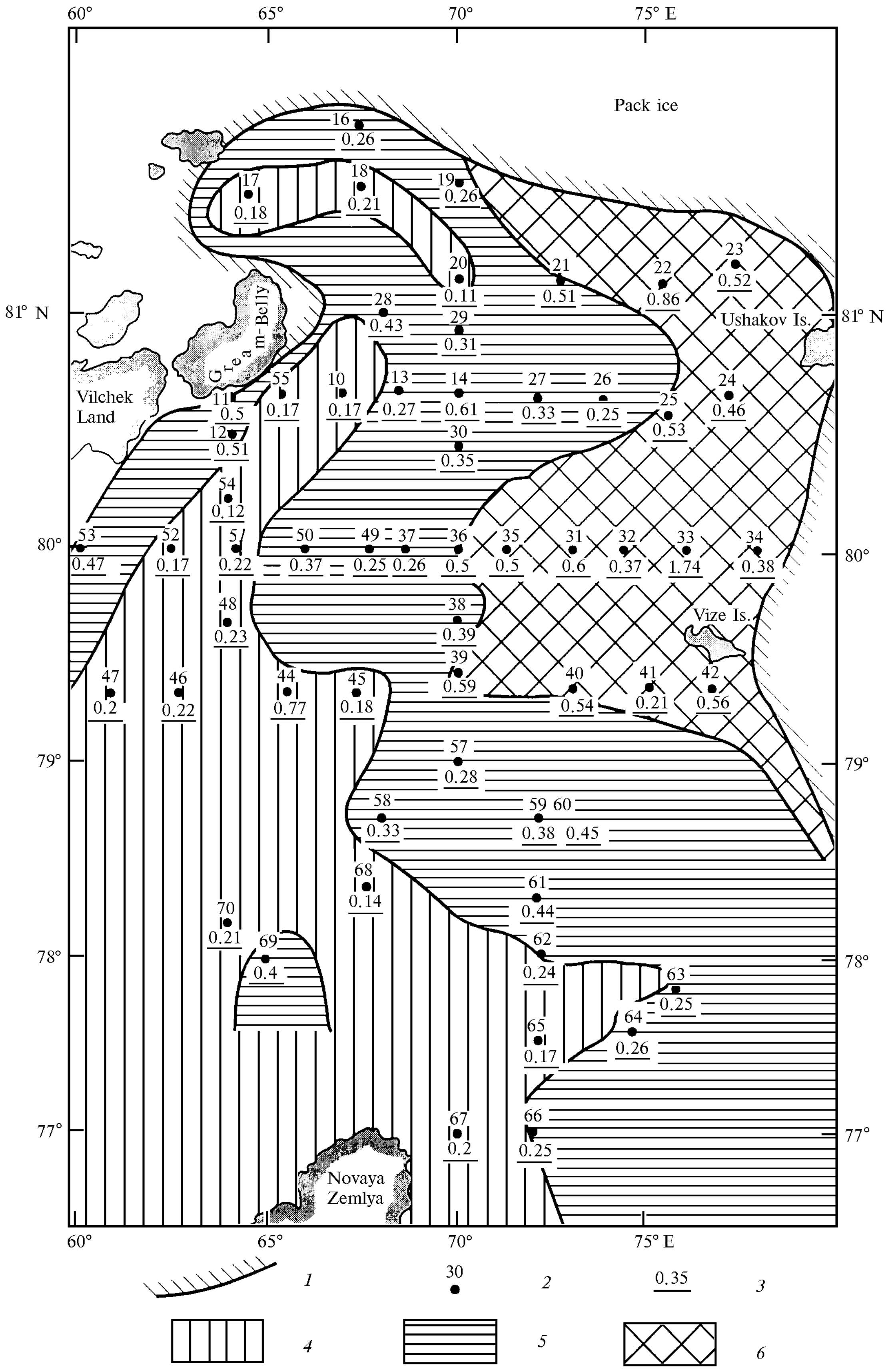

Fig. 7. Distribution of suspended matter in the surface water in St. Anna Channel in August 1994: ice edge (*1*); station numbers (*2*), the amount of suspended matter in mg/l (*3*): < 0.25 mg/l (*4*), 0.25–0.5 mg/l (*5*), > 0.5 mg/l (*6*) (Ref. 17).

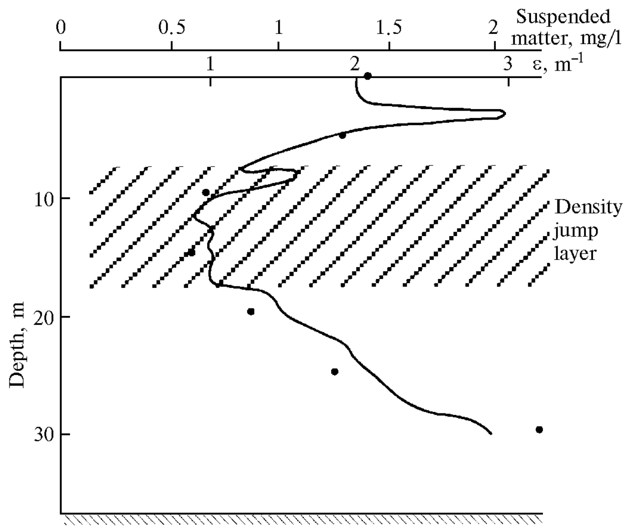

Fig. 8. Distribution of the suspended matter content and the extinction coefficient ε at station 4402 situated in the inner part of the Yenisei Bay (49th mission of *Dmitrii Mendeleev* RV, September 17, 1993): suspended matter (dots) and ε (curve).

Thus, the nepheloid layer is pronounced in the section from the mouth of Lena River (see Fig. 4); it is clearly seen in Kara Sea, in the section to St. Anna Channel (Figs. 6, 9, and 10), where the turbid water flows down from the upper part of the continental slope to the depth of 600 m (observations of August–September 1994),[16] and in Barents Sea (observations of August–September 1997 in the 11th mission of *Akademik Sergei Vavilov* RV, Figs. 11 and 12).[14,38]

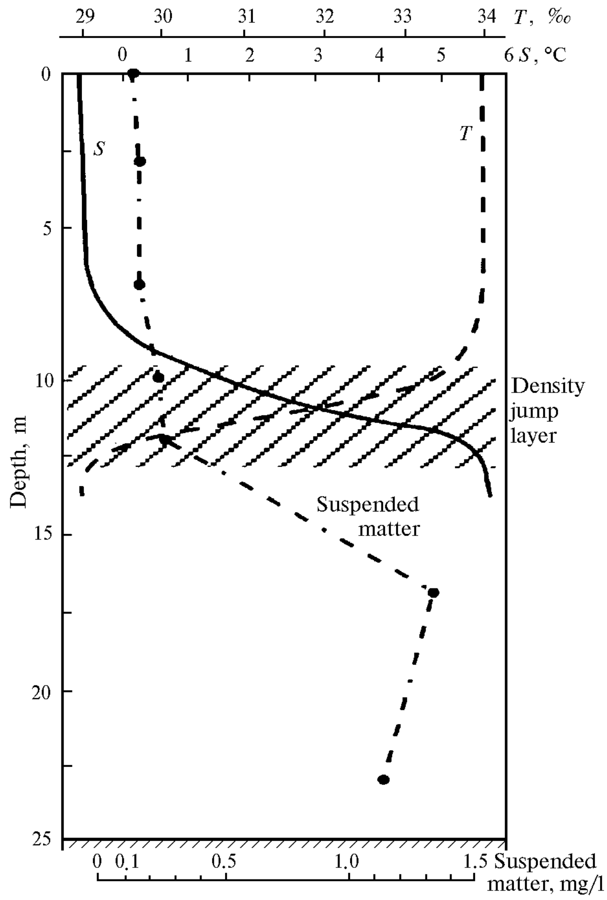

Fig. 9. Distribution of temperature (*T*), salinity (*S*), and content of suspended matter at the station 4392 in Baidaratskaya Gulf of the Kara Sea (49th mission of *Dmitrii Mendeleev* RV, September 6, 1993).

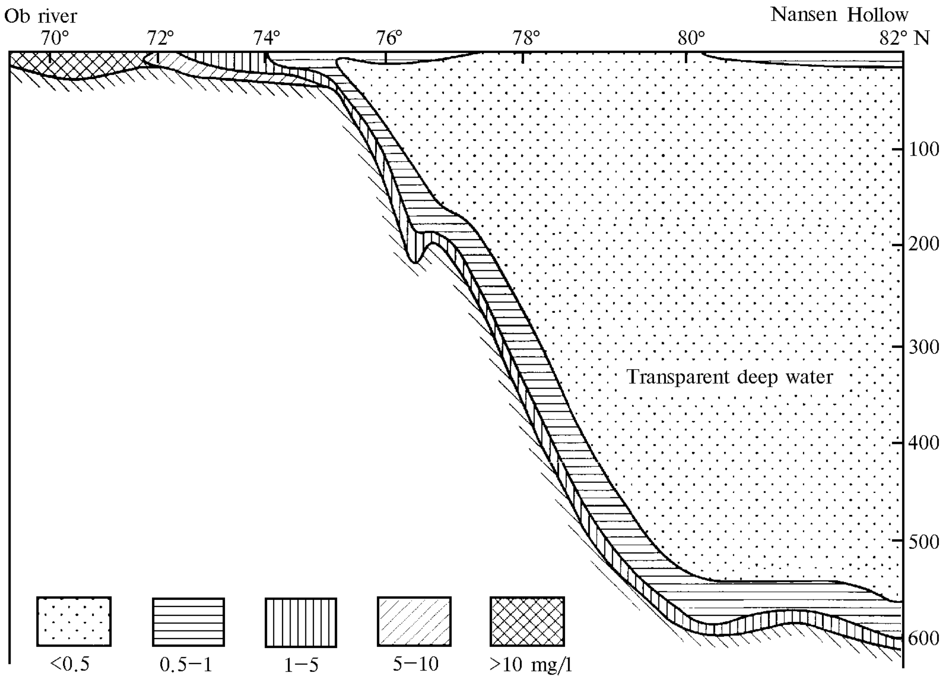

Fig. 10. Distribution of suspended matter in the section from the estuary of Ob River to St. Anna Channel in August–September (49th mission of *Dmitrii Mendeleev* RV and 9th mission of *Professor Logachev* RV) (Ref. 17).

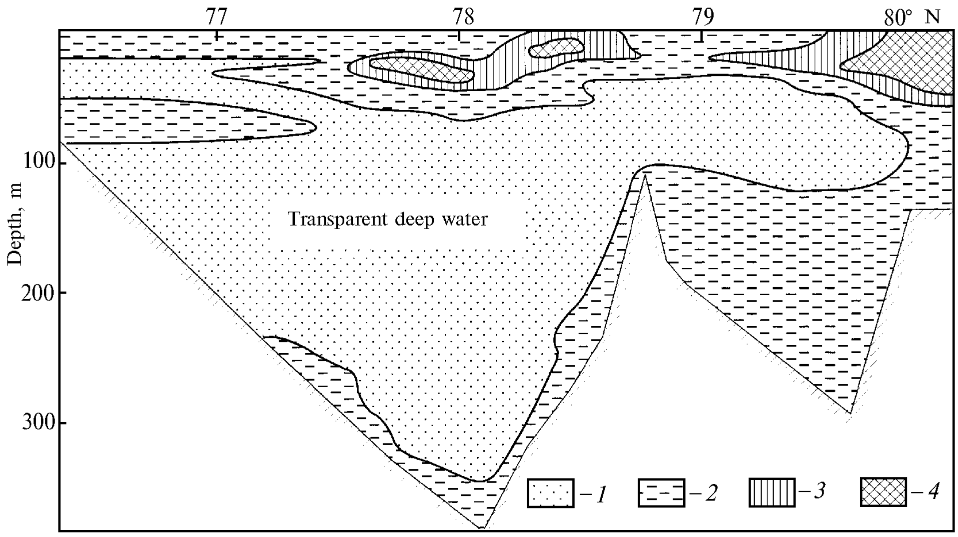

Fig. 11. Distribution of suspended matter in Barents Sea in the 60° E section, in mg/l: < 0.1 (*1*), 0.1–0.3 (*2*), 0.3–0.5 (*3*), > 0.5 (*4*) (Ref. 14).

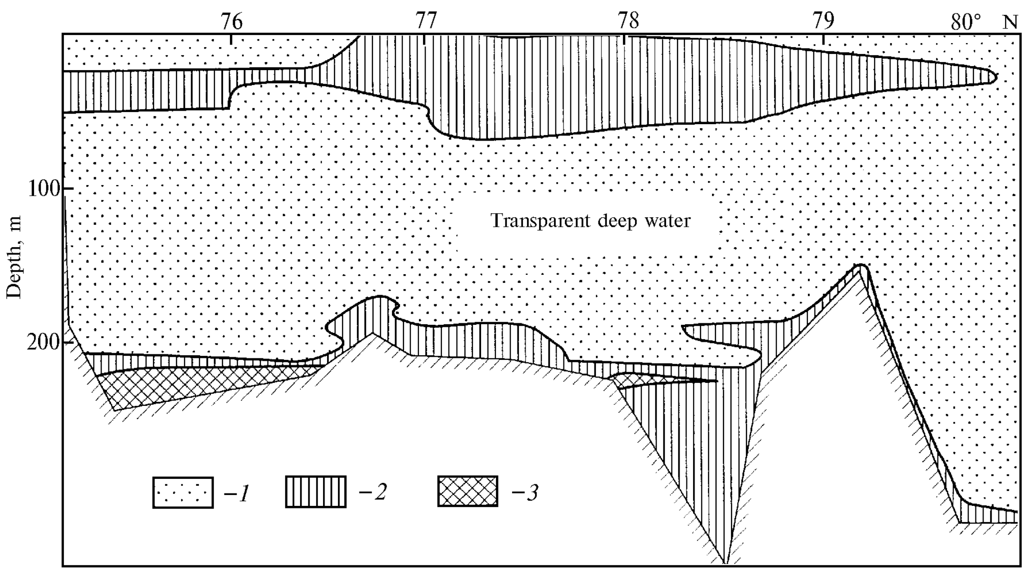

Fig. 12. Distribution of suspended matter in Barents Sea in the 40° E section, in mg/l: < 0.3 (*1*), 0.3–0.5 (*2*), > 0.5 (*3*) (Ref. 14).

The year-round observations of this phenomenon were first conducted for six years near the base of the continental slope of Norwegian Sea at the place of wreck of the atomic submarine *Komsomolets*.[24,25] Here we can clearly see two vertical layers of water enriched with suspended matter: the upper layer (up to 100 m) which is mostly associated with the distribution of phytoplankton and the lower layer achieving its maximum at the depth of 1440 m and deeper (Fig. 13). Detailed studies of hundreds of samples of suspended matter collected in this place showed that the composition of suspended matter from the upper layer differs significantly from that of suspended matter from the nepheloid layer. The suspended matter carried from the neighboring shelves of Barents Sea (that is, from the depth of 200 m) prevails in the nepheloid layer. This is also supported by the composition of foraminifers, siliceous organisms, etc.

Peculiarities of the nepheloid layer were completely revealed from analysis of suspended matter sampled with sedimentation traps (Fig. 14). In the composition of the bottom flow of the sediment, terrigenic material is of greatest significance, rather than a biogenic part, as would be expected from the study of the surface layer.

We have managed to map the nepheloid layer in this region and to estimate its thickness and trajectory of motion near the base of the continental slope. It turned out that the layer gradually moves in the northwards direction to the Fram Strait, reaches the slopes of Spitzbergen, and then likely finds its way to the Central Arctic.[24,39] Possible radioactive pollution from nuclear facilities of the submarine will follow this direction too; however, radioactive pollution was not detected during the whole period of observations.

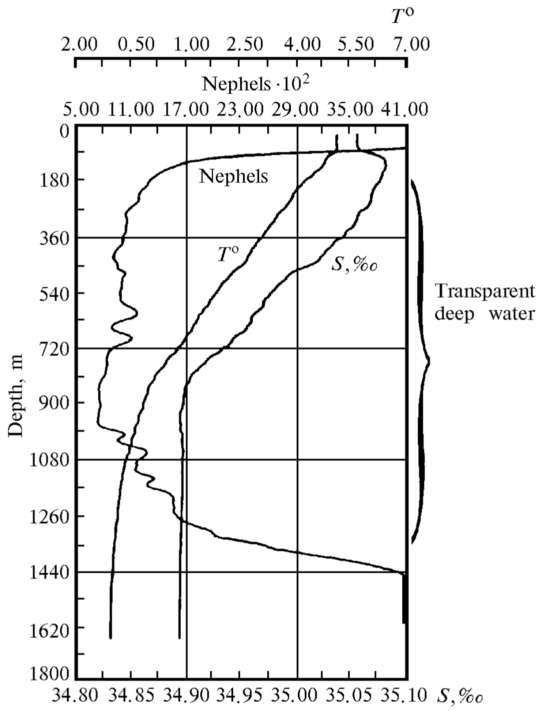

Fig. 13. Typical distribution of hydrophysical characteristics and turbidity at the place of wreck of submarine *Komsomolets* (Ref. 24).

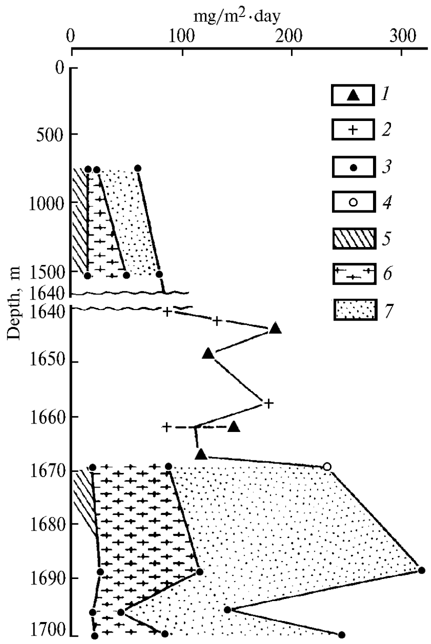

Fig. 14. Structure of the vertical flow of sediments at the place of wreck of submarine *Komsomolets*: station 2497 (*1*), station 2498 (*2*), station 3087 (*3*), station 3088 (*4*), organic substance (*5*), biogenic carbonate material (*6*), terrigenic material (*7*) (Ref. 25).

Conclusions

In recent years Russian scientists have performed simultaneous study of the hydrooptics, suspended matter, plankton, and physical fields of the Arctic seas with application of new methods, including satellite observations. This study allows the following conclusions to be drawn:

1. In the Arctic, in contrast to other climatic zones, the main part of suspended matter, which determines the optical properties of water, is delivered by rivers and then trapped and redistributed by sea ice.

2. A small contribution of plankton to formation of the optical properties of the Arctic water is caused not only by low temperature, ice cover, and polar nights, but also by insignificant amounts of incoming biogens. The latter is caused by weak development of chemical airing in frozen water collection areas, absence of Azotobacter in cold soil, as well as fixing of a great part of phosphor by C-sorbent and Fe-sorbent in marginal filters.

3. The Arctic rivers, including the great Siberian rivers, are characterized by low content of suspended matter: most often from 20 to 50 mg/l, while the mean content of suspended matter for the rivers in the world is 490–500 mg/l.

4. The mean content of suspended matter in the surface water of Arctic seas is 0.1–0.5 mg/l, and in the Central Arctic it is 0.1 mg/l as low and even lower.

5. The direct and close relation has been found between the content of suspended matter and the extinction coefficient. This relation is described by the equation of linear regression. The correlation coefficient for seas in the Eastern Arctic varies within 0.90–0.97. The Arctic seawater is characterized by high transparency approaching the transparency of water in the tropical Atlantic (except for the western part of Barents and Norwegian Seas).

6. Long-term studies in the Arctic at river–sea sections showed that the main part of suspended matter in river waters deposits near mouths within the 20v isohaline, where avalanche sedimentation of the suspended matter and, correspondingly, water filtering occur (marginal filter by Lisitsin, 1994). About 90–93% of the river suspended matter and about 30–40% of dissolved elements deposit in the marginal filters of rivers. These filters are multistage with changing gravitational, physico-chemical, and biological parts.

7. Beyond the marginal filters, the sea ice mostly affects the water optical properties that are primarily determined by suspended matter. As ice thaws in summer and recedes to the north, phytoplankton and zooplankton filters (MIZ phenomenon) are developed along the ice edge. This frontal zone moves northwards in spring and summer, ice releases the sediment (its content in ice is roughly 10–20 times higher than in water) and biogenic elements contained in it, which are needed for plankton. A wide zone of increased turbidity arises, which gradually moves toward outer parts of the shelf.

8. The Arctic seas are characterized by seasonal behavior with main changes occurring in two or three summer months. The peak of river discharge gives way to the peak of plankton florescence and in fall to the peak of ice formation. Ice formation is accompanied by formation of heavy water enriched with salt "pressed outB of the sea water at freezing (cold distillation). In winter the peaks of formation of in-water ice arise in large polynias. These peaks correspond to the winter peaks of formation of heavy water enriched with suspended matter (nepheloid layer).

9. The heavy water enriched with suspended matter (nepheloid) flows down along the bottom in the general direction to the continental slope. Then the bottom nepheloid layer flows down the slope (cascading) and spreads out by isopycnic surfaces. Most dense water enriched with the suspended matter spreads near the bottom.

10. It is characteristic of the distribution of the nepheloid layer in the Central Arctic that it is influenced with the income of Atlantic intermediate water, which comes from the Fram Strait and then bends around the deep-water part of the Arctic in the counter-clockwise direction (contour stream). This water was traced by the optical properties and suspended matter at the depth from 200 m near the Fram Strait down to 1700 m in the Canadian Hollow.

11. Thus, the Arctic seas are characterized by a pronounced two-layer structure of water with two maxima of suspended matter content: on the surface (above pycnoridge) and near the bottom (nepheloid layer).

12. The whole year-round observations in the deep layer with sedimentation traps in combination with satellite observations (SeaWiFS) allow one to reveal the changes in optical properties and content and composition of suspended matter not only on the surface and in depth (3D studies), but in time (4D studies) as well. This opens up new possibilities for the year-round optical monitoring and forecasts.

13. According to the available data, though yet incomplete, the transparency of the Arctic water under the pack ice is close to or higher than the transparency of water in the Sargasso Sea (the content of suspended matter less than 0.1 mg/l).

14. The regularities discussed above determine the distribution and composition of suspended pollutants on the surface and in depth in different seasons.

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