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MARINE CHEMISTRY

# The Distinguishing of the Ob and Yenisei Waters in the Desalinated Lenses of the Kara Sea in 1993 and 2007

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**Abstract**—In 1993 and 2007 when the expeditions of the Shirshov Institute of Oceanology were performed in the Kara Sea, a significant part of its aquatic area was occupied by lenses of desalinated water. The freshwater is supplied by the runoff of the Ob and Yenisei rivers, as well as by meltwaters. The report considers the features of the freshwater chemical transformation in the sea. It is shown that the contribution of meltwaters is small in the highly desalinated lenses (with salinity below 15‰) and the freshwater is supplied by the riverine runoff. It is also shown that, under definite conditions, it is possible to determine the relative shares of the Ob and Yenisei waters using the chemical parameters (the silicon and alkalinity). The data of 1993 when two lenses as such were found in the sea were confirmed; at that, the waters of the Yenisei and Ob rivers were prevailing in the western and northeastern lenses, respectively. In 2007, one lens was found in the treated area of the sea. It is shown that the chemical characteristics of the freshwater in the lens appeared to be sufficiently different from those of the Ob river but similar to the Yenisei river's characteristics according to the data of 1993. A map of the Ob's and the Yenisei's water spreading over the sea's aquatic area is presented.

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## INTRODUCTION

The formation of the surface waters in the Kara Sea is provided by the proper Kara Sea waters; the voluminous riverine runoff; and, during the warm season, the meltwaters. The relative contribution of one or another source is considerably variable in time and over the sea's aquatic area. One of the objectives of cruise 54 of the R/V *Akademik Mstislav Keldysh* was the study of the genesis and extension of the Kara Sea's surface waters as characterized by the great contribution of the Ob and Yenisei rivers. The chemical parameters of the waters of these rivers—the silicon concentration (Si) and the alkalinity value (Alk)—are different, which, in several cases, allows one to distinguish the areas of the prevalence of the waters from one or another river. The use of chemical tracers is especially promising for the seasons of the low bioactivity of the waters.

The report aimed to compare the situation of the riverine water's extension in the sea in 1993 and 2007 and to consider the conditions under which one can distinguish the areas of the prevalence of the waters from one of the rivers in the surface layer of the Kara Sea.

## MATERIALS AND METHODS

We analyzed the data obtained in September 2007 during cruise 54 of the R/V *Akademik Mstislav Keldysh* and compared them to those from cruise 49 of the R/V *Dmitry Mendeleev* (September 1993). The procedures of the sampling and the chemical analyses of the samples are given in [7]. In all, the data obtained at 49 hydrological stations (the route's scheme and the location of the stations are given in [4]), 13 samples collected with a pump while the vessel was moving, and 18 samples collected at the coasts of the bays of the Novaya Zemlya Islands were used for the study.

**The features of the riverine water's extension over the sea's aquatic area in the different years.** In the western and central parts of the sea where the expedition's route passed, the main sources of freshwaters are the Ob Bay (including the Ob, Taz, and Pur rivers) and the Yenisei Gulf. We consider these freshwater sources as the main ones and refer to them for short as the Ob and Yenisei. The sea receives 41% of the total land runoff into the Arctic Ocean or 56% of the riverine runoff in the Siberian sector of the Arctic. The total runoff of the rivers flowing into the Kara Sea amounts to 1350 $km^3$/year; within this volume, the shares of Ob and Yenisei account for 530 and 603 $km^3$/year, or 37 and 45%, respectively [8, 12]. Undoubtedly, the waters of these rivers constitute the primary component of the freshwater runoff and cause the pronounced desalination of the surface waters in the Kara Sea.

In September 2007, in the western part of the Kara Sea, a region of the surface water desalination with an area of about 250 000 $km^2$ was observed with the salinity being below 25‰ and it being separated from the Ob and Yenisei river mouths [4, 18]. The thickness of the desalination layer (the lens) amounted to about 10 m.

In the core of the desalination region adjoining the Novaya Zemlya coasts, the salinity decreased to values below 15‰. In [4] considered the hydrophysical features of the lens waters, and the circulation of the sea surface waters under different wind conditions in 2007 formed this lens. In this report, the authors used the chemical parameters of the lens' waters (especially the Si and Alk) to identify the sources of its freshwaters. These are the Ob and Yenisei's riverine runoff, the meltwaters, and the surface runoff from the land. The problem of distinguishing the riverine water using other chemical parameters besides the salinity is topical for all the Arctic seas and, especially, for the Kara Sea with its enormous riverine runoff. The use of the chemical parameters of the waters (particularly, the Si content) started quite a long time ago. The distribution of the riverine waters obtained by means of these parameters is sometimes different from that obtained from the salinity [11]. With the accumulation of data, the notion concerning the riverine water's extension was complicated: at first two; then three; and, finally, four types of the distribution of the zones of the riverine runoff's influence in the Kara Sea were distinguished [10]. These were the cases when (1) the riverine waters are supplied to the central part of the sea and transferred eastwards under the winds of the western and northwestern directions; (2) when the riverine waters are extended westwards under the winds of eastern bearings; (3) when the riverine waters are extended southwestwards and occupy many of the areas of the southwestern part of the sea up to 71°N, which are usually free of the influence of the riverine runoff; and (4) when large areas of the sea's surface are desalinated by the riverine runoff and separated from the freshwater sources (the Ob and Yenisei river mouths) with a saline water inflow from the northeast [13]. Water patches of high salinity and low specific alkalinity (with their correlation coefficient being about 0.87) are observed at the Novaya Zemlya coasts and in the central part of the sea. This takes place under strong and steady northeastern winds.

As a characteristic example of type (4), [10, 13] present the situation registered by the specialists of the Arctic and Antarctic Research Institute in July 1993. In September of the same year, the expedition of the Shirshov Institute of Oceanology (IO RAS) during cruise 49 of the R/V *Dmitry Mendeleev* observed the same two still separated lenses of desalinated waters. The lenses were quite different from each other in their chemical characteristics and minimum salinities (10 and 14‰ [1]), so an attempt was made to identify the sources of these waters using the salinity–silicon and salinity–alkalinity relationships [14]. The result obtained was unexpected: in one of the lenses, the Ob waters were prevailing with those of the Yenisei in the other. Moreover, the Ob lens appeared to be located northward and eastward of the Yenisei lens.

Before this study, no attempts were made to identify the different riverine waters using their chemical parameters (particularly, by using their Si and Alk values). This was because the mixing of the riverine waters in the sea hinders the potential for the separation and autonomous existence of the lenses of the Yenisei and Ob waters, the presence of waters of another genesis in the aquatic area (the ice melting and the meltwaters from the Novaya Zemlya Islands), the seasonal Si and Alk variability from the flood to the low-water period, the interannual variability of these parameters because of the variations in the riverine runoff volume, and the high Si utilization appearing in the summer in the Ob Bay [10]. Taking into account all these circumstances, one may agree with Pivovarov that, in general, i.e., in all the seasons and for all the types of the extension of the riverine waters (especially for type (1) of eastward extension), the Yenisei and Ob riverine waters cannot be identified using the common chemical parameters such as the silicon and alkalinity. However, at some favorable conditions such as those in 1993 and, as seen below, in 2007, it is feasible and, as we think, necessary, because this provides the fine details of the riverine water's motion. Moreover, the distinguishing of the Ob and Yenisei water's impacts upon the Arctic basin should be of special interest in view of the development of the projects of the partial Ob water withdrawal for transferring to Central Asia [5].

The attempt to identify the waters in 1993 was incited by the mentioned separate occurrence of two water lenses. In 2007, the identification of the waters become possible, in many respects, due to the ability to overcome the above difficulties to a considerable degree. Thus, the hydrophysical features of the sea's surface waters are considered in [4]. This study showed that the massive runoff of the Yenisei floodwaters takes place in June considerably exceeding that of the Ob river, which provides the possibility of the temporary prevailing of the Yenisei over the Ob waters, their separate existence, and their transfer under steady winds.

The difficulties in determining the hydrochemical features of the different waters still take place, but they are also surmountable.

1. The fact is used that, in the summer with the lower courses of the rivers, the content of silicon and the alkalinity value are lower in the Ob than those in the Yenisei River, and both of these parameters are applicable for the water's identification. The difficulty consists in the variability of these parameters such as according to the river's width [2, 6, 17] from one station to another even under no impact of the seawater [6, 7]. This circumstance has yet to be considered below in the discussion of the results of the surveys.

2. Interannual variations of the chemical parameters in the rivers take place but may be included.

3. Seasonal variations of the values are present, but they are observed mainly in the desalinated areas of the

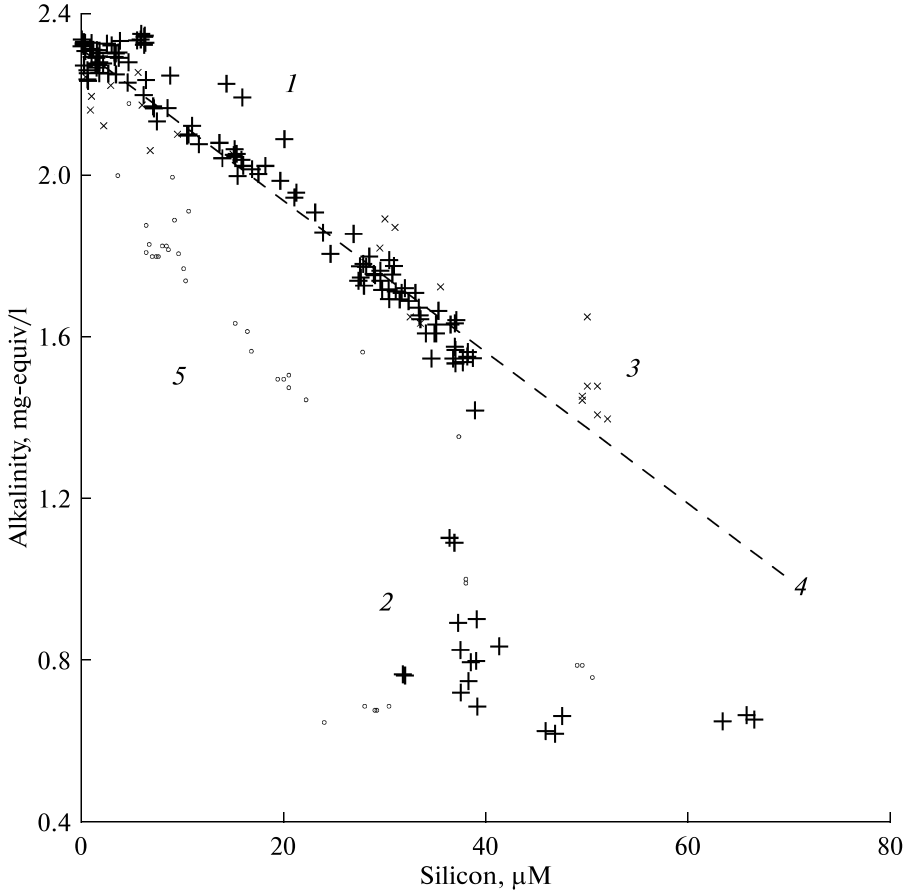


**Fig. 1.** The relationship between the silicon concentration and the alkalinity value in the surface layer of the Kara Sea waters (the data of 2007).

*1*—for the main part of the sea; *2*—for the Ob Bay area. *3*—for the lens of Yenisei waters; *5*—for the lens of Ob waters (the data of 1993). *4*—the interpolation line of the Yenisei waters for both years.

Ob Bay and the Yenisei Gulf, and they markedly decrease at the water supply to the sea proper owing to the mixing of the winter and the flood waters (of increased and decreased values of the hydrochemical parameters, respectively).

4. The decrease of the silicon concentrations caused by the biological processes is observed exclusively in the Ob Bay for a relatively short time (under a month). At the same time, silicon concentration falls as such are registered very rarely in the Yenisei Gulf [10], and the waters with these parameters are not transferred out of the gulf. Moreover, the silicon content in the summer is lower in the Ob than in the Yenisei river; therefore, the further decrease under the biological processes increases the contrast between these waters. At the same time, the alkalinity is almost not affected by the biological processes as such. Nevertheless, the difficulties in the separation of the waters due of course still persist.

**The identification of the desalinated waters in 2007.** A map of the distribution of the desalinated waters in the Kara Sea in 2007 is given in [4]. The fact that not all the desalinated waters are uniform is well seen from the diagram of the Si–Alk relationship in the surface layer (Fig. 1) plotted according to the data of both 2007 and 1993 [14]. Here, the water layer of about 10 m thickness, including the upper mixed quasi-uniform layer, is considered, as well as a part of the underlying halocline, namely, the part in which the decrease of the Si concentration is observed. Deeper, the salinity still increases, but, at the same time, the growth of the Si concentration begins not because of the desalinated and marine water mixing but due to the dissolution of dead diatom algae. These points were not included into the diagram, as well as the data on the brooks at the Novaya Zemlya Islands.

The data of 2007 (denoted as +) were obtained in the sea (denoted as *1*) and in the Ob Bay (*2*). It is seen from Fig. 1 that the points in area *1*, as well as those of 1993, belong to the eastern lens of desalinated waters (denoted as × and *3*) falling onto the same straight line (*4*), which shows the Si–Alk relationship in the case of the prevalence of the Yenisei water in the marine and riverine water mixture. The group of points *5* conforms to the northeastern desalinated lens of 1993 in which, according to [14], the Ob waters were prevailing. It is seen from Fig. 1 that the regression line drawn via these points might be extended for considerably low Si and Alk values being characteristic for Ob Bay. The points *2* (at the outlet from the Ob Bay in 2007) also show the transition from the Yenisei to the same Ob water. At that, the points of the minimum Alk values, i.e., of almost fresh waters, show a pronounced scattering of the Si concentration (both in 2007 and in 1993), as stated above. At the same time, during the discharge of the Ob water to the sea, the parameters are averaged, which is testified to by the decrease of the point scattering in the hidden lines of mixing (i.e., at salinities of 5–15‰).

The question remains to be answered concerning whether this diagram may be considered without the inclusion of the ice melting. In the Kara Sea, about 1000 km$^3$ of ice are formed and melt annually (with partial northwards transfer), which conforms to about a 1 m layer of desalinated water over the entire aquatic area of the sea. This value roughly coincides with the volume of the riverine waters; therefore, the meltwaters should exert a significant influence upon the sea's hydrochemistry. The parameters of the meltwaters formed (Si and Alk) may be evaluated by means of ice samples (we deal only with the one-year ice, because it supplies the bulk of the meltwater). According to the surveys at the North Pole 34 polar station [9], the average parameters of the ice as such amounted to 5‰ for the salinity, 1 μM for the Si, and 0.4 mg-equiv/l for the Alk; at that, the salinity dependence of the Alk values was linear with an almost zero remainder term. From this, one may conclude that really no changes in the ice's chemical composition as regards the brine supply took place in this case. The waters as such, whether they were found during the cruise, should give points in the left lower corner of Fig. 1. They should be well pronounced in Fig. 2 as well, in which the correlation of the Si concentration and the salinity is shown. At the same time, in Fig. 3, where the correlation of the Alk and salinity is shown, these waters should not be so pronounced, especially at high salinity values. However, the data [9] present, as one may say, an ideal case, because all the ice throughout the whole survey time existed at very low temperatures. For the Kara Sea, the conditions may be diverse; particularly, the ice's salinity, depending on the conditions of its formation, may vary within 2–15‰, and the partial changing of the brine's composition may take place during its flow down with the formation of local sites with increased specific Alk values [15]. However, the existence of the ice as such, in principle, makes no difference, because the meltwaters, as a rule, are not registered in their pure form owing to the long duration of the ice's melting and the instability of the thin highly desalinated lenses under the wind mixing. For example, in 1993,

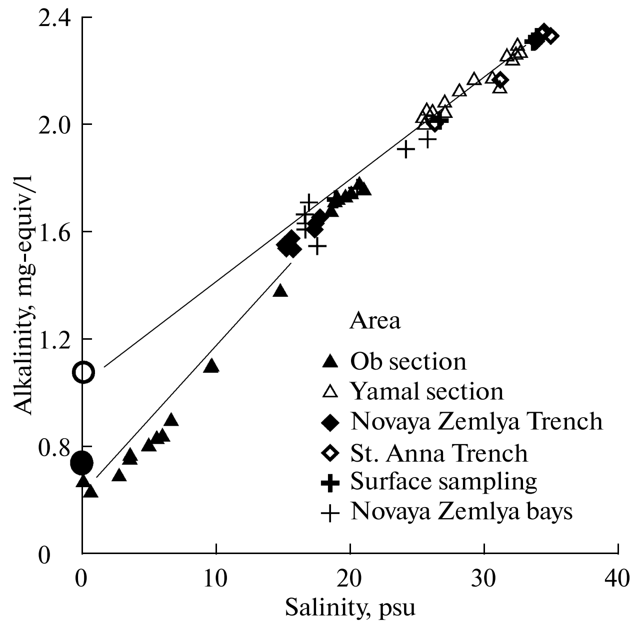


**Fig. 2.** The dependence of the total alkalinity value (mg-equiv/l) and the salinity (psu) for the surface waters of the studied area of the Kara Sea.

The black circle is the average alkalinity value in the Ob riverine water according to the data of the previous studies. The light circle is the average alkalinity value in the Yenisei riverine water according to the data of the previous studies.

the minimum salinity in the southern part of the sea, i.e., in the region subjected to no riverine runoff impact, amounted to 28‰ in the layer of about 5 m thickness. Thus, the bulk of the meltwaters gets mixed with the underlying waters causing their desalination (by about 2–5‰), and the proportional decrease of the Alk values at low Si concentrations occurs. These waters may occupy their own location in the aquatic area or they may be the basis into which the riverine waters flow, but they do not prevent one from distinguishing the Ob and Yenisei waters, which is especially reliable in the case of the presence of pronounced desalination in the lenses (10–15‰).

Thus, in view of Fig. 1, the situation of 1993 may be characterized as the presence of the separated desalinated lenses in the aquatic area: one of mainly the Yenisei and the other of the Ob water (in full compliance with [14]). In 2007, the desalinated water over the entire surveyed western and central parts of the aquatic area was uniform and mainly of the Yenisei origin, and the Ob water was concentrated at the outlet of the Ob Bay (unfortunately, no surveys were carried out in the eastern part of the sea).

**The calculation of the contribution of the individual sources to the formation of the surface waters.** For the calculation mentioned, a few procedures are usable. First, there is the regression analysis that was applied for the treatment of the data of cruise 49 of the R/V

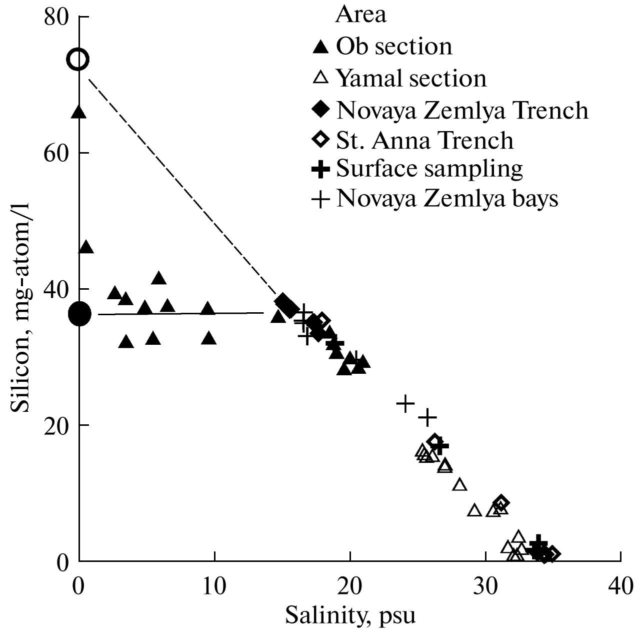


**Fig. 3.** The dependence of the dissolved silicon content (μg-atom/l) and the salinity (psu) for the surface waters of the studied area of the Kara Sea.

The black circle is the average silicon content in the Ob riverine water according to the data of previous studies. The light circle is average silicon content in the Yenisei riverine water according to the data of previous studies.

*Dmitry Mendeleev* in 1993 [14]. For different areas of the sea, regression equations were derived for the alkalinity values' and the silicon contents' correlation with the salinity.

$$C = A_0 + SA_1, \quad (1)$$

where $A_0$ and $A_1$ are empiric coefficients, $S$ is the salinity, and $C$ is the value of any chemical parameter.

The value of the absolute term $A_0$ may be treated as the parameter value at zero salinity and, in this case, points to the Alk or Si values in the riverine waters. This approach allows one to distinguish the transformed Ob and Yenisei waters with reasonable certainty and to characterize their contributions to the formation of the surface waters.

In considering the data of 2007, the regression method was applied to separate the areas of the sea distinguished by their hydrophysical and hydrochemical parameters [7]. These were the section in the eastern part of the sea towards the Yamal Peninsula, the section across the Novaya Zemlya Trench, the surveys in the bays of the Novaya Zemlya Islands, the section across the St. Anna Trench, and the section in Ob Bay. The values of the alkalinity and the dissolved silicon content at zero salinity (the absolute term $A_0$) are given in the table. It is seen that, in the areas of the St. Anna and Novaya Zemlya trenches, these values are close to the average alkalinity values and the dissolved silicon content in the Yenisei waters. The $A_0$ values close to the average alkalinity values and the dissolved silicon content in the Ob River were registered only in Ob Bay. In the section towards the Yamal Peninsula and in the Novaya Zemlya bays, the $A_0$ values for the silicon are close to its content in the Yenisei waters, but the "zero" alkalinity value is higher than that in the waters of both rivers. As to the waters of the Novaya Zemlya bays, this may be caused by the pronounced effect of the surface runoff from the coasts (The average alkalinity value of the freshwaters flowing down from the Novaya Zemlya Islands is about 2.2 mg-equiv/l). The reason for the significant increase of the zero alkalinity as such in the section towards the Yamal Peninsula is unknown because there are no data available to characterize the chemical composition of the surface runoff in this area.

Another approach was proposed and tested for the waters of the Pechora Sea in [3] with the assumption that the value of the conservative (or quasi-conservative) parameter $C_0$ under the mixing of the waters should be described with the following equation:

$$C_0V_0 = C_1V_1 + C_2V_2 + C_3V_3 + \ldots, \quad (2)$$

where $V_i$ is the volume of the water mass $i$, and $C_i$ is the value of the corresponding parameter. In view of $V_0 = \Sigma V_i$,

Equations of the relationships of the total alkalinity (mg-equiv/l) and the dissolved silicon content (μg-atom/l) with the salinity (psu units) for different areas of the Kara Sea according to the data of cruise 54 of the R/V *Akademik Mstislav Keldysh*

| The sea area | Regression equation for the Alk value | Regression equation for the Si |
|---|---|---|
| Section towards the Yamal Peninsula | Alk = 1.155 + 0.040S | Si = 68.5 – 2.056S |
| Novaya Zemlya section | Alk = 0.953 + 0.039S | Si = 59.9 – 1.458S |
| Novaya Zemlya bays | Alk = 1.037 + 0.035S | Si = 61.3 – 1.570S |
| Section across the St. Anna Trench | Alk = 0.899 + 0.040S | Si = 72.9 – 2.083S |
| Section in Ob Bay | Alk = 0.543 + 0.059S | Si = 44.4 – 0.777S |

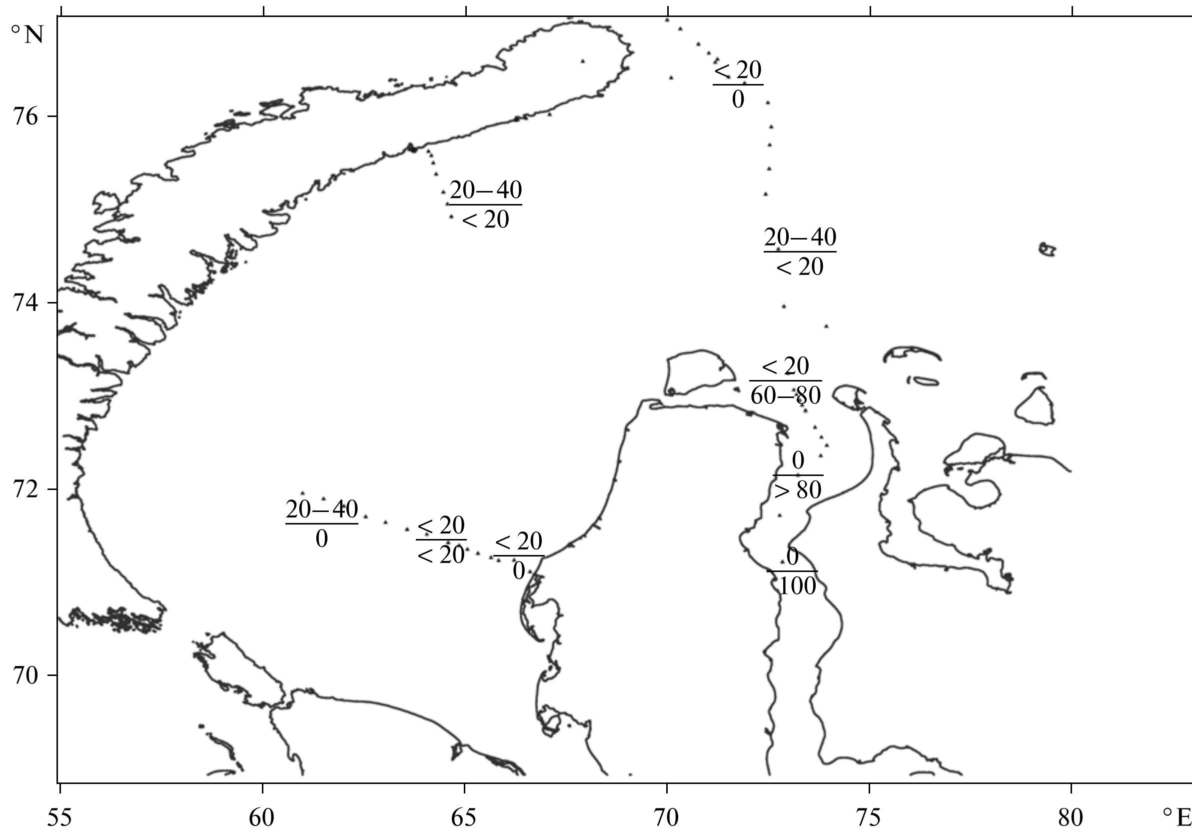


**Fig. 4.** Relative contribution (%) of the waters of the Yenisei and Ob rivers (the upper and lower figures, respectively) to the formation of the Kara Sea's surface waters according to the data of the surveys during cruise 54 of the R/V *Akademik Mstislav Keldysh*.

one may express the relative contribution for each individual water mass as $K_i = V_i/V_0$. Hence, the equation takes the form

$$C_0 = \Sigma(C_iV_i/\Sigma V_i) = \Sigma(K_iC_i). \quad (3)$$

Assuming that the sum of the relative contributions of each water mass is $\Sigma K_i = 1$, we obtain a system of linear equations that may be solved for $K_i$ if we know the values of the $C_i$ parameters. At that, using the $N$ parameters, one may carry out the calculations for $N + 1$ water masses. The numerical solution of Eq. (3) with the calculation of the $K_i$ values was obtained for two, three, and four water masses. As the parameters, we selected the salinity, the silicon content, and the total titrated alkalinity (or the sum of the dissolved inorganic carbon $C_{tot}$). The latter value, because the bioactivity of the region is rather low and the inorganic carbon fraction involved into the photosynthesis only amounts to about 1–10% of its total content, may be considered with some assumptions as a quasi-conservative parameter, especially for a short time interval. Moreover, the features of the composition of the mass species of the high-latitudinal plankton cause the carbon being involved into the biochemical processes to a lesser degree than, e.g., the silicon commonly used as a tracer element [11, 13].

To calculate the shares of the individual sources using system of Eqs. (3), one must prescribe the values of the parameters for the different water sources. As said above, this is quite a complicated problem, especially for the waters of continental runoff. In this study, to characterize the Yenisei waters, the annual average data of [16, 17] were used. To characterize the Ob and marine waters, the average values for the endpoints of the river–sea mixing lines were used (Figs. 2 and 3), which conform to the surveys at stations 4993 and 4984, respectively.

The solution of system of Eqs. (3) using the data on the salinity, the Alk value, and the dissolved silicon content resulted in the following view of the distribution of the contribution of the Ob and Yenisei waters to the formation of the surface waters of the Kara Sea (Fig. 4). It is evident that, just after the discharge from the Ob Bay, the fraction of the Ob waters decreases to 20% and below and becomes practically zero at the northern extremity of the Novaya Zemlya Islands and in the western part of the sea. The Yenisei waters con-

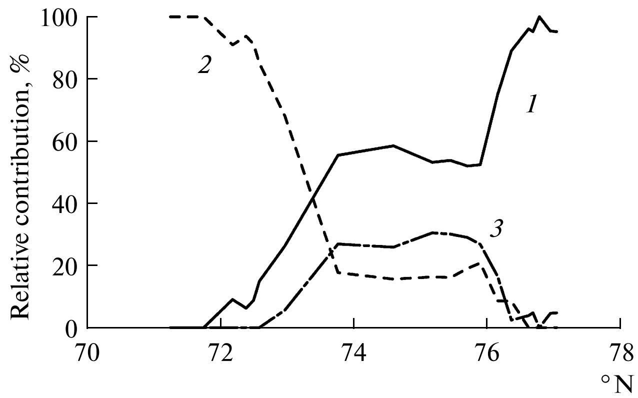


**Fig. 5.** Relative contributions of the waters of the open sea (*1*) and the Ob (*2*) and Yenisei (*3*) rivers to the formation of the surface waters in the Ob Bay–St. Anna Trench section.

stitute from 20 to 40% of the surface desalinated waters over most of the sea's aquatic area. Thus, in 2007, as in 1993, just after the discharge from the Ob Bay, the permeation of the Yenisei waters was registered [18]. This is seen well in Fig. 5. It shows the relative contributions of the different sources to the formation of the surface waters at the Ob Bay–St. Anna Trench section obtained by calculations using system of Eqs. (3). The fraction of the proper seawaters (curve *1* in Fig. 5) increases with the latitude from zero to the maximum of about 100% at 75°N. The Ob water fraction (curve *2*) decreases rapidly from 100 to 20% at 74°N. From 73 to 76°N, the contribution of the Yenisei waters increases (curve *3*).

## CONCLUSIONS

In 1993, the pronounced influence of the Ob waters was traced in the northeastern part of the sea and immediately at the outlet of the Ob Bay [14]. It was this area where one might register with certainty their occurrence in 2007 as well. Unfortunately, the surveys of 2007 were not extended further east than 75°E, and the authors cannot tell whether the Ob runoff was carried off to the eastern part of the sea. However, in the north of the sea, the relative contribution of the Ob runoff to the formation of the surface waters was almost zero, unlike the situation of 1993. The evaluation of the relative contributions of the waters of the different origins in the western and southwestern parts of the sea is very complicated because of the continuing shortage of knowledge about the chemical composition of the surface runoff from the Yamal peninsula and the Novaya Zemlya Islands. As the surveys in Blagopoluchiya and Techenii bays showed [7], the characteristics of this runoff are extremely variable. The extension of the riverine water over the sea's aquatic area observed both in 2007 and 1993 is not completely explained by any of the published schemes of the riverine runoff's transfer.

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