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MARINE CHEMISTRY

Features of the Continental Runoff Distribution over the Kara Sea

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Abstract—This paper considers different types of the continental runoff distribution over the Kara Sea depending on hydrological and meteorological processes based on 1993–2014 expedition data of the Shirshov Institute of Oceanology. The results of calculating the relative contribution of fresh water from several sources (the Ob and Yenisei rivers and melted ice) using hydrochemical parameters are also given.

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INTRODUCTION

The Kara Sea is the receiving basin for the runoff of Siberia's two largest rivers: the Ob and Yenisei [4]. In addition, the sea also receives waters from the Pur, Taz, Pyasina, and other rivers. The total runoff of rivers emptying in the Kara Sea is 1350 km^3/yr, 82% is Ob and Yenisei waters [15]; i.e., the waters of these rivers make up the majority of freshwater runoff. The study of river water propagation over the sea basin and estimation of the contribution of each of these rivers in the surface layer structure is of great significance.

The problem of river water propagation over the sea basin has been discussed at least since 1930s [26], and the alkali–chlorine ratio is one of the major indicators of river runoff. In addition to the hydrochemical parameters, the distribution of continental runoff is also estimated from hydrophysical data, results of satellite analysis, and modeling [6, 8, 37]. The boundaries of the continental runoff distribution can also be determined using the hydrochemical characteristics of mixing waters, in particular, the dissolved silicon content [21, 26]. According to the literature data, this boundary is determined by the 10 μm-silicon isoline [23, 24]. Another reliable criterion for the presence of continental runoff waters is the alkalinity/salinity (Alk/S) ratio. The change in salinity can be also caused by melting ice (marine, river, and continental), atmospheric precipitates, and permafrost degradation. However, changes in the Alk/S (or Alk/Cl) ratios are mainly controlled by river runoff. $Alk/S > 0.06$–0.08 confidently indicates the significant contribution of river waters [15, 22].

Several schemes of continental runoff propagation in the Kara Sea basin are known from the literature data (Fig. 1). In particular, three schemes—eastern, central, and western—are proposed in [7, 16]. An additional southwestern type, distinguished in [25], can be combined with the western type. Naturally, such river runoff propagation is mainly determined by wind [7]. The second important factor is the volume of fresh waters supplied from the Ob, Yenisei, and other rivers (this work took into account only waters of the two former rivers, which make up over 80% of the total freshwater runoff in the Kara Sea).

Only the total input of fresh waters (including continental runoff, atmospheric precipitates, and melted ice) can be estimated from physical parameters alone (salinity and temperature). Chemical parameters should be applied to determine the contribution of individual sources of fresh waters. Stunzhas was the first to attempt separation of Ob and Yenisei waters in the surface layer of the Kara Sea [28]. Using salinity–alkalinity and salinity–silicon regression equations, Stunzhas showed that the desalinated lens found in autumn 1993 near the northern coast of Novaya Zemlya [2] consists of Yenisei waters. Work on distinguishing the waters of different sources in the Kara Sea was continued using the equation of mixing of quasi-conservative substances [13].

It was demonstrated in previous works that the values of the total alkalinity (Alk), content of dissolved inorganic carbon (C_{tot}), and dissolved silicon are more suitable for determining the origin of high-latitude surface waters, because they are the most sensitive indicators of continental runoff and better match the quasi-conservative conditions than other hydrochemical parameters [3, 13, 28].

In addition to the areal distribution of continental runoff over the sea basin, it is also important to take into account the vertical influence of fresh waters on the hydrological and hydrochemical structure of the Kara Sea. Analysis of results of 271 CTD soundings during the expeditions of the Shirshov Institute of Oceanology from 1993 to 2014 showed that the desali-

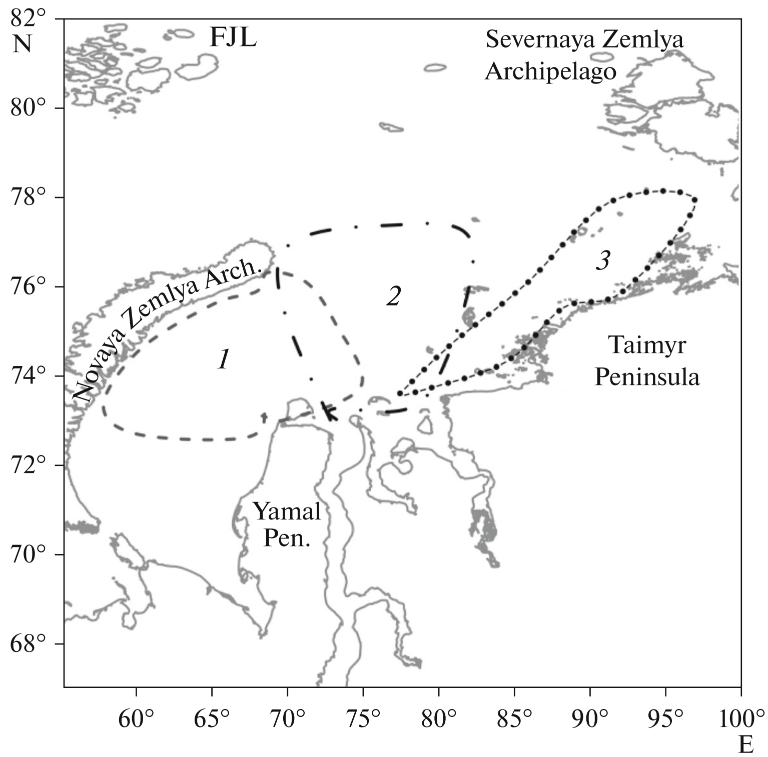

Fig. 1. Types of distribution of river runoff in Kara Sea: *1*, western type (combined with southwestern type); *2*, central type; *3*, eastern type.

nation of the seawater surface layer occurs within a range from 3–5 m to 15–20 m.

MATERIALS AND METHODS

All data used for calculations were obtained during a comprehensive oceanographic expedition of the Shirshov Institute of Oceanology, Russian Academy of Sciences, in 1993 [9], 2007 [30], 2011, 2013, and 2014. In all these expeditions, works on hydrological stations were supplemented by sampling during as the vessel moved. The obtained distribution of the fields of hydrochemical parameters and vertical hydrochemical structure of waters are presented in detail in [10–12]. Materials of 2013 and 2014 expeditions have not been published yet. In these expeditions, samples were analyzed using standard techniques recommended for marine hydrochemical studies [19, 20, 27], while hydrological data (temperature and water salinity) were obtained from CTD sounding. The NCEP/NCAR reanalysis (http://www.cdc.noaa.gov) was used to obtain data on the dynamic influence of wind on the surface sea layer [35]. This work was also based on river discharge data available free of charge at http://www.arcticgreatrivers.org/. This is the Arctic Great Rivers Observatory Project, which has collected data on runoff from the Ob, Yenisei, Lena, Kolyma, Yukon, and Mackenzie rivers since 1999 to the present. Hydrographs of the Ob and Yenisei rivers are shown in Fig. 2.

Several methods can be applied to study the contribution of separate sources to the formation of surface waters. The first is regression analysis. Regression equations for alkalinity and silicon content versus salinity were obtained from natural observations for different sea regions:

$$C = A_0 + SA_1, \tag{1}$$

where A_0 and A_1 are empirical coefficients, S is the salinity, and C is the content of some chemical parameter.

The value of the free term A_0 can be interpreted as the value of the parameter at zero salinity and in the given case implies the content of salinity or silicon in river waters.

Another approach is based on the assumption that the value of the conservative (or quasi-conservative) parameter C_0 during mixing will be described by the following equation:

$$C_0V_0 = C_1V_1 + C_2V_2 + C_3V_3 + \dots, \tag{2}$$

where V_i, is the volume of the ith water mass, while C_i is the value of the corresponding parameter; taking into account that $V_0 = \sum V_i$, the relative contribution of each separate water mass can be expressed as $K_i = V_i/V_0$. Then the equation is transformed as follows:

$$C_0 = \sum(C_iV_i/\sum V_i) = \sum(K_iC_i). \tag{3}$$

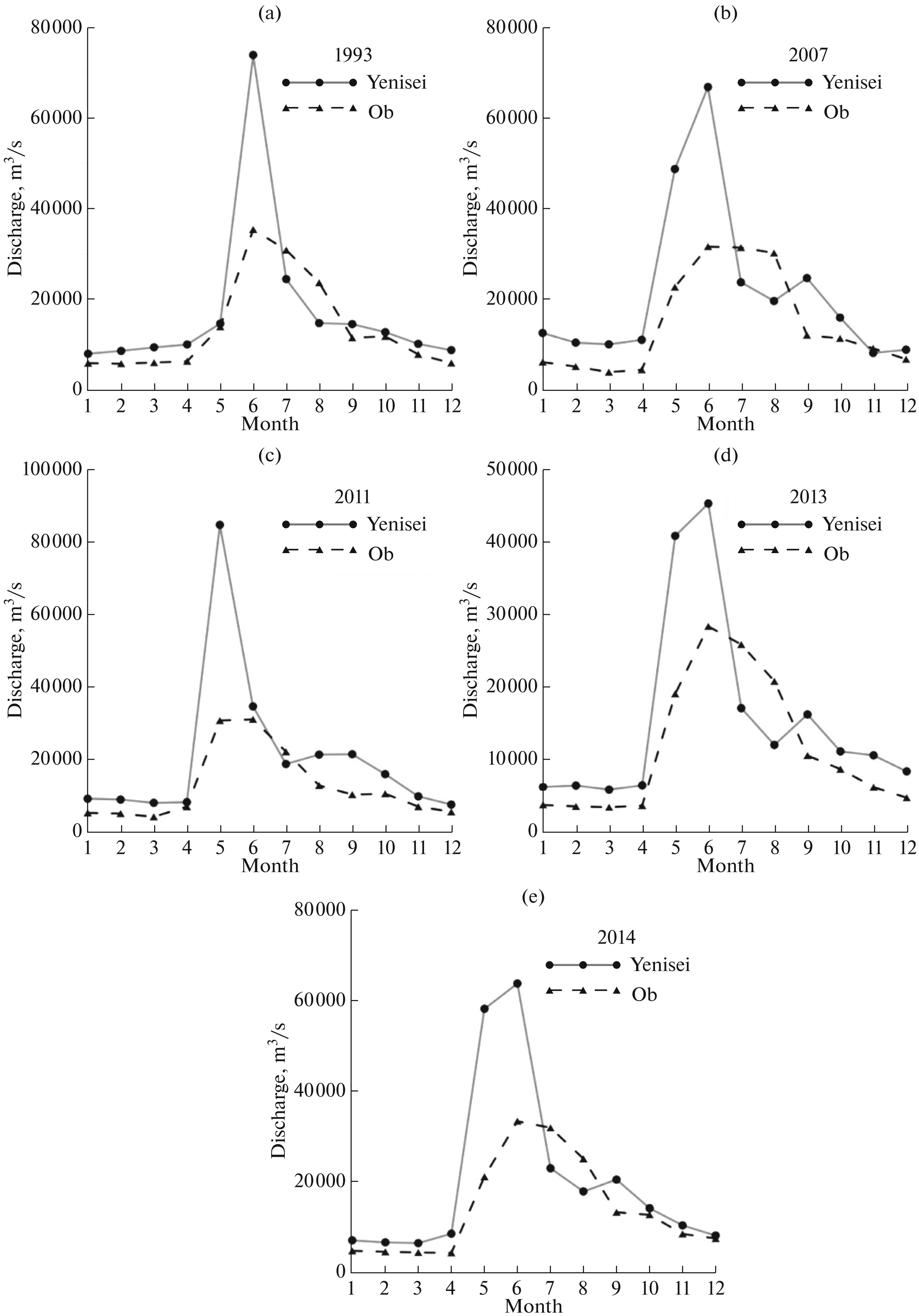

Fig. 2. Monthly discharge of Ob and Yenisei rivers in (a) 1993, (b) 2007, (c) 2011, (d) 2013, and (e) 2014. Data from Arctic Great Rivers Observatory Project http://www.arcticgreatrivers.org/.

Values of mineralization, alkalinity, and content of dissolved silicon and inorganic carbon in water of near-estuary areas of Yenisei and Ob bays obtained during expedition works and calculated from regression equations

Year	River	Measured parameters (using salinity minimum)				Using regression equation B/A ($y = aS + b$)		
		Sal	*Alk*	Si	C_{tot}	*Alk*	Si	C_{tot}
1993	Ob	*0.745**	0.712	36.83	9.20	0.681 0.049	36.89 –0.449	8.75 0.567
1993	Yenisei	0.047	1.226	81.00	15.34	1.094 0.034	74.24 –1.834	13.64 0.402
2007	Ob	0.049	0.656	65.21	8.16	0.584 0.052	65.21 –0.887	8.16 0.597
2011	Yenisei	0.068	1.017	107.44	12.62	0.965 0.041	86.79 –2.536	11.96 0.471
2013	Ob	0.227	0.980	29.94	12.34	1.028 0.040	49.92 –0.581	12.70 0.473
2014	Ob	0.036	0.398	9.39	5.51	0.669 0.054	64.16 –1.428	8.56 0.620
2014	Yenisei	1.094	0.727	55.24	9.21	0.583 0.054	53.88 –0.874	7.47 0.639

* Calculated using regression equation

Assuming the total of the relative contribution of each water mass is $\sum K_i = 1$ and knowing the values of the C_i parameters, we obtain a system of linear equations that can be solved with respect to K_i. The use of N parameters yields the calculations for $N + 1$ water mass. The technique for calculating the contribution of different sources to the formation of surface desalinated layer using the mixing equations was described in [3, 32]. While preparing this work, we modified this method. First, we calculated the fraction of fresh waters, which is required to construct the profile of the surface desalinated layer. The calculations were performed to a depth of 20 m until the maximum salinity observed in the surface layer during the entire period of works was reached. Using the mixing equation and hydrochemical characteristics of the open part of the sea, we calculated the content of C_{tot}, dissolved silicon, salinity, and *Alk* for hypothetical water required to form the waters of the surface layer, without separation of different sources. The fractions of the Ob, Yenisei, and melted ice were calculated for the hypothetical water. It was proposed that exactly these waters account for the majority of freshwater runoff in the sea basin.

This method works successfully for the wide compositional diversity of water sources. The chemical composition of river runoff is particular for each river and is determined by the types of soil and rocks that compose the underlying surface of the drainage area. This work is aided by the fact that the Ob and Yenisei rivers differ sharply in the chemical composition of waters [14, 34, 36]. Since the Ob River flows over swampy plains, its waters contain more nitrogen compounds and dissolved carbon dioxide than the Yenisei waters, which, in turn, are enriched in silicon and carbonate carbon as compared to the Ob [11].

The main difficulties in applying this method are related to the choice of values of the corresponding parameters (C_i) for the end mixing points (Yenisei and Ob rivers and melted ice). These difficulties are related to the mixing of river waters in the sea, the presence of fresh waters of other genesis (ice melting, melted ice from islands and continents); as well as seasonal variability in the chemical composition of river waters between flood and low water periods, as well as annual variability of the parameters due to variations in the volume of river runoff. However, it should be taken into account that most river waters in this region are removed during the flood period, while the contribution of low waters is quite insignificant (Fig. 2). Taking into account the significant volume of Yenisei Bay and, especially, Ob Bay, the results of measuring C_{tot}, dissolved silica, salinity, and *Alk* in the freshwater part of these bays in the given year, if available, can be taken as the values for these two rivers. If no observations were made in the river estuary, we applied free terms of regression equations for surface waters in the near-estuary region of this river. The table lists the data on these parameters used in our calculation. These data were obtained either directly during cruises or were calculated using the free term of the regression equation.

Naturally, the composition of river waters differs from that of melted ice. The effect of the ice formation and melting on the proportions of main ions is insufficiently studied. However, some researchers believe that the ice formation can be accompanied by the partial precipitation of carbonates and their accumulation

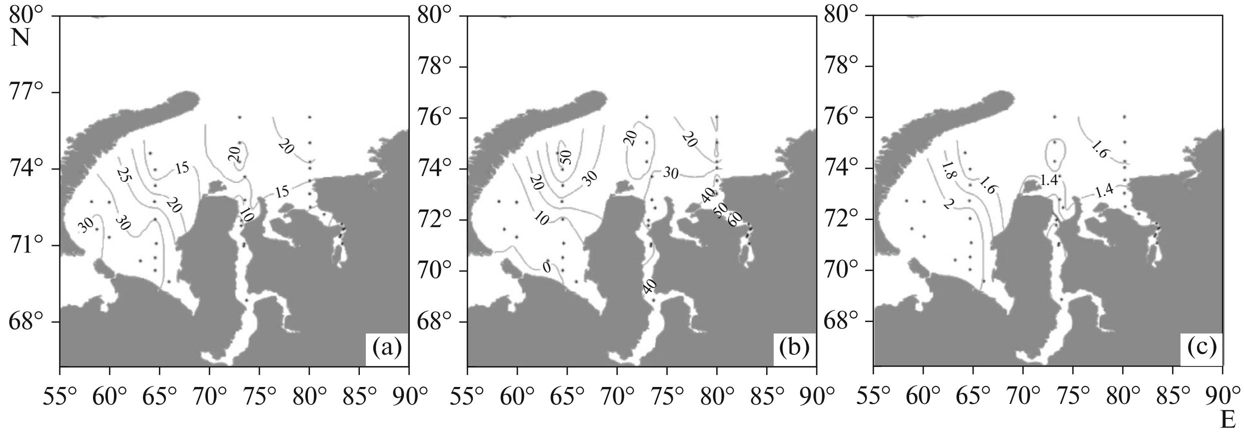

Fig. 3. Distribution over sea surface in 1993. (a) Salinity, psu; (b) dissolved silicon, μM; (c) total alkalinity, mg-equiv/L.

in ice. In this case, water in the brine cells will be depleted in the carbonate carbon, while ice melting can cause enrichment of water in carbonate material [18, 31, 38]. In [17, 39, 40], it was proposed to take the average C_{tot}, dissolved silicon, salinity, and value of *Alk* of melted ice for this region obtained in experiments on sea ice melting as the values of these parameters for melted ice. However, we believe that this approach is not correct. First, chemical data on the melted ice strongly depend on the age and origin of the ice and many other factors. In addition, this approach ignores the role of atmospheric precipitates, and partially, continental ices. In our calculations, the salinity and content of the chemical parameters in so-called "melted ice" were taken to be zero. Neglecting variations in the proportions of main ions during ice formation, salt cells during ice melting interact with water to form seawater with characteristics similar to the surface waters of the given area. Thus, the assumption of the "zero" composition of melted ice leads to insignificant underestimation of the fraction of melted and atmospheric waters in the surface sea layer.

RESULTS AND DISCUSSION

Below we present the results of studies of continental runoff propagation in the Kara Sea, as well as the results of calculating the contribution of Ob and Yenisei waters and melted ice in the desalination of the surface sea layer obtained during the 1993–2014 expeditions of the Institute of Oceanology.

Hydrological–Hydrochemical Characteristics of the Surface Layer

Cruise 49 of the R/V *Dmitrii Mendeleev* (August 14–October 15, 1993). As seen from Fig. 3a, the maximum desalination of the offshore part (below 15 psu) is observed northwest of the estuary of Ob Bay. In the west, the desalination boundary can be drawn between the 20 and 25 psu isolines from the western coast of Yamal to the eastern coast of Novaya Zemlya. From the east, the expedition studies were limited to a transect along 80° E, beginning from the estuary of Yenisei Bay. Along the transect, the surface salinity varied from 0 psu in its southern part to 20 psu at the northern station. Thus, we cannot determine the eastern boundary of river water propagation. The salinity distribution and delineation of the boundaries of continental runoff propagation have been confirmed by hydrochemical data. In particular, the distribution of total alkalinity in Fig. 3c corresponds to that of water salinity. In addition, this figure well illustrates the strong difference between the fresh waters of the Ob and Yenisei rivers: Ob Bay waters, which have a lower carbonate content, are characterized by an alkalinity of 0.6–0.8 mg-equiv/L, whereas Yenisei waters have an average salinity of 0.8–1.0 mg-equiv/L. Similar results were obtained by analyzing the silicon distribution in the surface layer. The western boundary of the river water propagation along the 10 μM isoline, like in the previous case, runs from the western coast of Yamal to the eastern coast of Severnyi Island of Novaya Zemlya (Fig. 3b). A remarkable feature of the surface layer is a sufficiently high (over 50 μM) silicon content at the northern station of the transect along 65° E. Such a high silicon content in combination with highly desalinated waters has not been reported yet. Correspondingly, continental origin was proposed for surface waters of this region [28]. Moreover, the alkalinity–salinity and silicon–salinity relations allowed the authors to suggest the predominance of the Yenisei water in this sea basin.

Cruise 54 of the R/V *Akademik Mstislav Keldysh* (9–30 September, 2007). Judging from the salinity distribution in September 2007 (Fig. 4a), the propagation of river waters is similar to that found during the 1993 expedition. The western boundary of river runoff influence extends from the western coast of the Yamal Peninsula to the supposedly eastern coast of Novaya

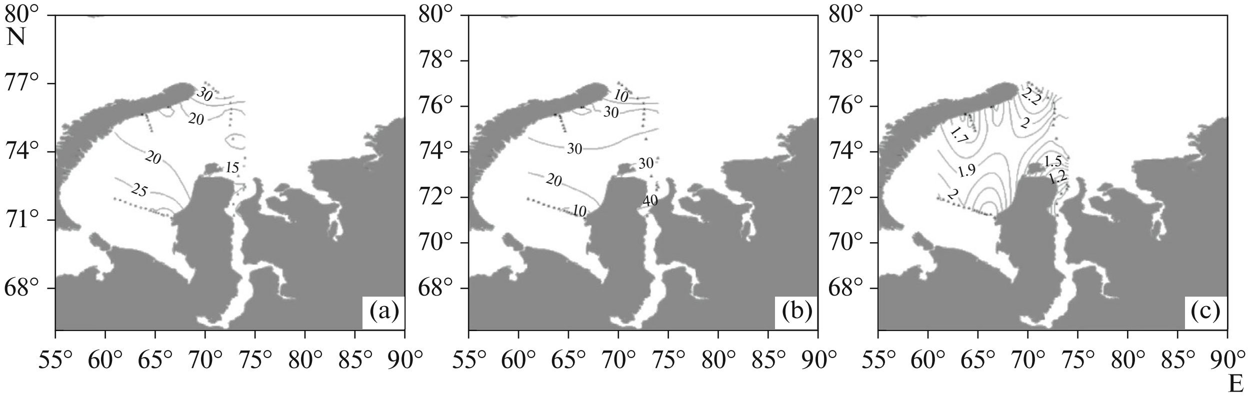

Fig. 4. Distribution over sea surface in 2007. (a) Salinity, psu; (b) dissolved silicon, μM; (c) total alkalinity, mg-equiv/L.

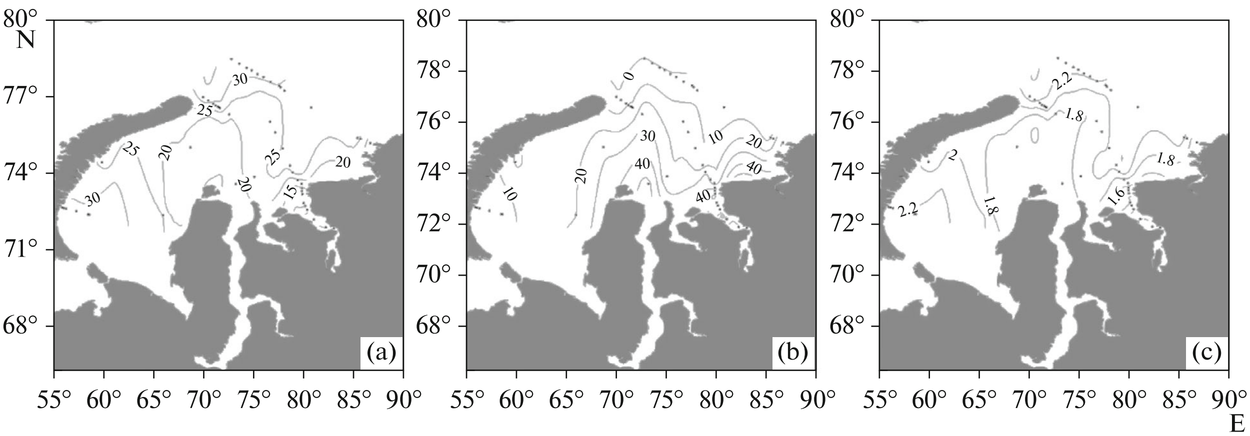

Fig. 5. Distribution over sea surface in 2011. (a) Salinity, psu; (b) Dissolved silicon, μM; (c) total alkalinity, mg-equiv/L.

Zemlya. This is confirmed by the distribution of dissolved silicon and total alkalinity. (Figs. 4b, 4c). The area over the western spur of the St. Anna Trough in the northern part of the studied area is characterized by salinity typical of water in the central Arctic Basin. The hydrochemical characteristics of this water (approximately 2.4 mg-equiv/L total alkalinity and less than 10 μM silicon) confirm this assumption. The boundary of the desalinated layer is situated south of 76° N. The eastern boundary of continental water propagation was not discovered during this expedition. Reanalysis of wind action in the Kara Sea area (NCEP/NCAR data) makes it possible to trace the parameters of atmospheric circulation during expedition works. Data on wind force and direction indicate that strong winds (over 15 m/s) in September repeatedly changed their direction over Ob Bay from north to south and vice versa. Thus, river runoff from the bay was localized between 72° and 73° N. The estuary of Ob Bay has a salinity of 10–12 psu (Fig. 4a), whereas the central part of the studied basin has a salinity of 18–20 psu. A quite high silicon content (30 μM) in the surface water was also observed near the estuary of the bay (Fig. 4b). At the outlet of Ob Bay, the total salinity was approximately 1 mg-equiv/L (Fig. 4c), which demonstrates the quite strong effect of Ob waters.

Cruise 57 of the R/V *Akademik Mstislav Keldysh* (September 14–October 04, 2011). The salinity distribution during the expedition (Fig. 5a) shows strong desalination of the central part of the sea basin and a quite narrow band east of the estuary of Yenisei Bay. The boundary of desalination reaches the northern termination of Novaya Zemlya in the north, distributed to 65° E in the west, and bordered by the easternmost station near the Taimyr Coast.

The area with only fresh water throughout the entire vertical section was reached in Yenisei Bay, which is confirmed by CDT sounding and hydrochemical determinations. The southwestern part of the sea is characterized by saline waters above 30 psu. The same is true of the St. Anna Trough, to the north of Novaya Zemlya. Sea waters (27 psu) penetrate from the north toward Yenisei Bay, thus presumably restricting the desalinated waters to the Taimyr coast.

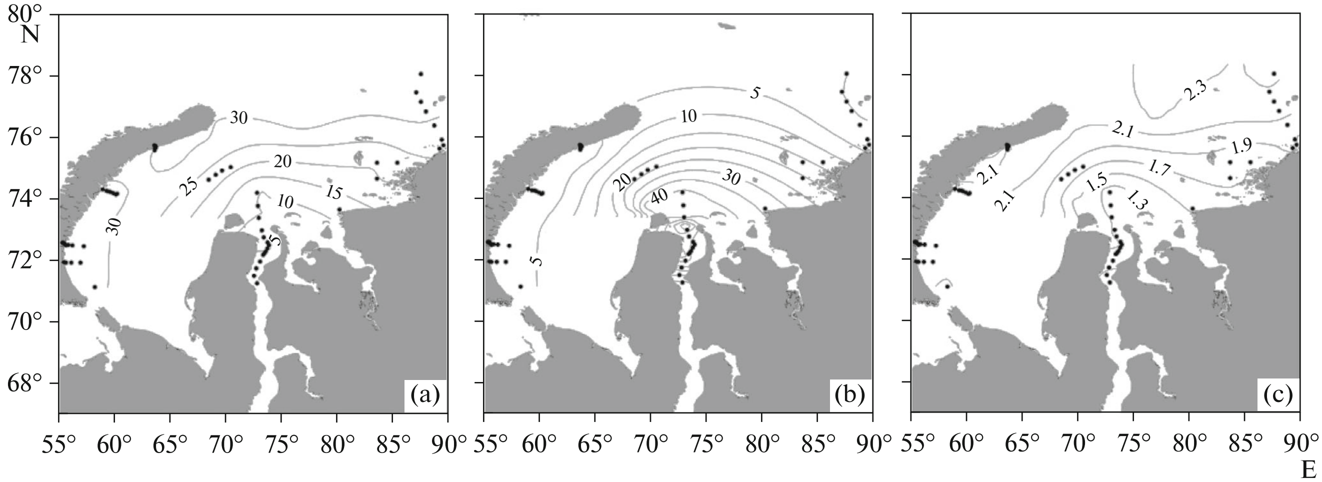

Fig. 6. Distribution over sea surface in 2013. (a) Salinity, psu; (b) dissolved silicon, μM; (c) total alkalinity, mg-equiv/L.

The above-described salinity distribution is consistent with the silicon distribution in the surface sea layer (Fig. 5b). Maximum silicon contents (over 100 μM) were recorded in Yenisei Bay and corresponded to Yenisei River waters with zero salinity. Judging from this parameter, river waters were widespread over the sea basin during expedition studies. The 10 μM isoline extends quite far westward from the Ob–Yenisei coastal waters, is located at the latitude of Cape Zhelaniya of Novaya Zemlya in the north, and passes approximately 300 km from the estuary of Yenisei Bay in the northeast.

The boundaries of the desalinated layer are well emphasized by the total seawater alkalinity (Fig. 5c). It should be noted that, judging from the distribution of this parameter, pure seawater (alkalinity of 2.3–2.4 mg-equiv/L) unaffected by continental runoff occurs only in the northern part of the studied area, between the eastern and western spurs of the St. Anna Trough.

Cruise 125 of the R/V *Professor Shtokman* (September 3–21, 2013). It is seen from the salinity distribution (Fig. 6a) that the Ob–Yenisei coastal waters are strongly desalinated and the salinity to the north of Ob Bay accounts for only 10–12 psu. The 24 psu isohaline taken as the desalination boundary in 2013 runs much farther to south and closer to the estuaries of the bays than during the above-mentioned expeditions, which presumably indicates the central (isolated) type of river runoff propagation. In the northern and western parts of the sea basin, the surface layer is characterized by a salinity of 30 psu, which suggests advection of Arctic waters in the Kara Sea from the north and, possibly, of Barents Sea waters through the Kara Gates [7]. Conclusions on the central type of river water propagation are confirmed by data on the distribution of dissolved silicon in the surface sea layer (Fig. 6b). This parameter reaches 60 μM in the offshore part of Ob Bay, accounts for 40 μM at 74° N, and gently decreases in seawater to the north, west, and east. The 10 μM isoline marks the boundary of river water spreading and practically coincides with 24-psu isohaline. The distribution of the total alkalinity in the surface layer shown in Fig. 6c confirms the central-type distribution of river waters. Noteworthy is the sufficiently high alkalinity in the Ob bay waters, in the southern stations of the section. The average multiyear value of the total alkalinity for the Ob Bay waters is 0.6 mg-equiv/L, whereas the minimum value in 2013 was 0.9 mg-equiv/L. This suggests that this expedition did not reach pure river waters, while the waters of the southern station reveal the influence of seawater.

Cruise 128 of the R/V *Professor Shtokman* (August 11–September 8, 2014). A schematic map of salinity distribution in surface layer compiled using CTD sounding data (Fig. 7a) clearly determines the boundaries of the continental runoff propagation in the basin. In particular, the clearly expressed desalinated (up to 10–12 psu) area in the Ob–Yenisei coastal waters propagates from Yamal to 65° E in the west, and almost to 90° E in the Taimyr coastal area in the east.

Such a distribution was recorded at the beginning of the expedition, in the first half of August. In addition, unlike the Ob River discharge, which corresponded to the multiyear distribution, the Yenisei discharge during the flood period was below the average multiyear value (around 60000 m^3/s). At the same time, this value was preserved at the same level in May and June (Fig. 2), whereas the flood period usually peaks in June. Thus, we can conclude that the Ob and Yenisei rivers yielded 62 and 42%, respectively, of the annual runoff during the first half of 2014.

Such a volume of continental runoff supplies a large amount of dissolved and particulate matter. Figure 7b shows the content of dissolved silicon in the surface layer. It is seen that the flow with the maxi-

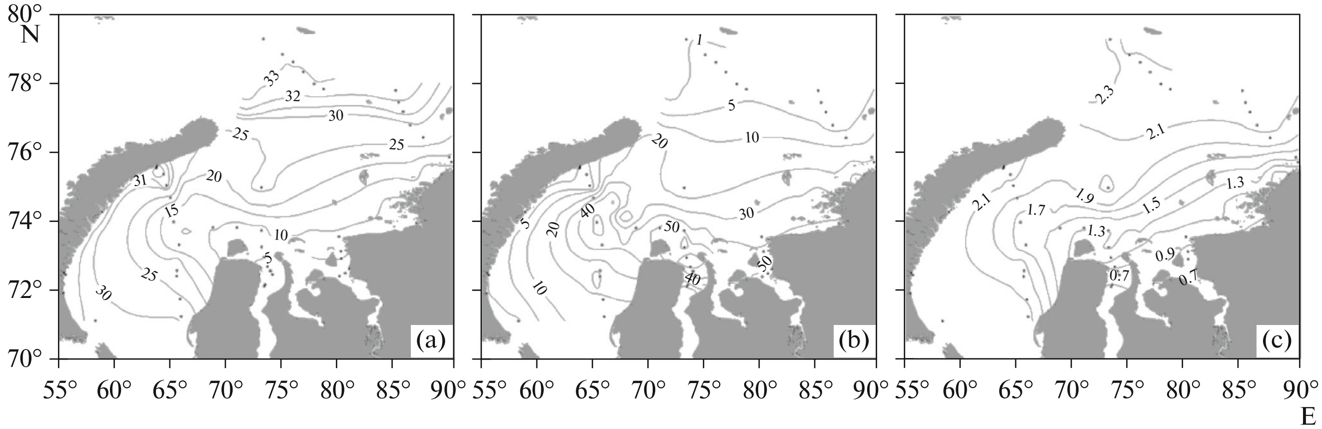

Fig. 7. Distribution over sea surface in 2014. (a) Salinity, psu; (b) dissolved silicon, μM; (c) total alkalinity, mg-equiv/L.

mum silicon content is directed west of the Ob and Yenisei estuaries. The silicon concentration in the estuaries reached 50 μM, whereas this region in general preserved silicon concentrations above 30 μM. The 10-μM isoline marks the quite strong effect of river runoff on the surface sea level in 2014: the western boundary strongly extends toward the Novaya Zemlya coast, whereas the northern boundary lies along the latitude of Cape Zhelaniya, Novaya Zemlya, and runs east, towards the Vil'kitsky Strait. The abovementioned distribution of river runoff to the sea basin is confirmed by the distribution of alkalinity in the surface layer (Fig. 7c). The position of river waters is reflected by the 2.1 mg-equiv/L isoline, which practically replicates the isoline of dissolved silicon distribution. It should be noted that the alkalinities measured in the offshore part of Ob and Yenisei bays (0.5–0.7 and 0.9 mg-equiv/L, respectively) are comparable with the average climatic characteristics for these areas [1, 5, 16, 33].

Contribution from Different Sources in the Formation of the Surface Desalinated Layer

1993. It is seen in Fig. 8a that around one-third of water of the desalinated area in the vicinity of Novaya Zemlya belongs to the Yenisei, around 20% (0.2 arb. units) belongs to fresh Ob runoff, and around 10% is supplied by melted ice. Correspondingly, the remaining half of the mixture is represented by surface water of the Kara Sea. The central part of the Kara Sea is mainly occupied by Ob Bay runoff. South of 73° N, it accounts for 30–40% (0.3–0.4 arb. units), whereas Yenisei water accounts for no more than 10% (0.1 arb. units). The hydrograph of the Ob and Yenisei rivers for 1993 (Fig. 2a), in general, is similar to the average multiyear plot of discharge of these rivers. But the main reason for the predominance of the Ob fresh water relative to the Yenisei waters in the surface layer is the seasonal variability of the discharge of the two largest Siberian rivers. The flood period for both rivers is peaked in June. During this period, the Yenisei discharge is over 2.5 times more than the Ob discharge. However, in July–August, the Ob discharge sometimes predominates over Yenisei one, and from September to the beginning of a flood period the discharge of both the rivers is practically identical. In addition, the Ob Bay estuary is closer to the considered area in the central part of the Kara Sea than the Yenisei estuary. Therefore, water from Ob Bay earlier enters the offshore part. Thus, due to the lower density, the Ob waters overlay seawater mixed with Yenisei waters, since the discharge of both rivers after the flood period is identical to or slightly lower than the Ob runoff. In this regard, data obtained during expedition indicate the predominance of the Ob water in the studied area. This effect will be noted in further descriptions of expedition studies and obtained results.

In general, it is difficult to determine the type of river runoff distribution during the 1993 expedition, because it bears features of both central (isolated) and western types. However, judging from the western boundary of salinity, silicon, and total alkalinity fields, this type can be determined as western.

2007. As seen from Fig. 8b, the Ob and Yenisei waters in the studied sea basin are weakly distinguished, in spite of the sufficiently intense flood period on both rivers (Fig. 2b). Based on the wind reanalysis, the fresh waters from Ob and Yenisei bays flowed eastward. Unfortunately, no works were carried out east of Ob Bay. Therefore, it is impossible to distinguish the contribution of different waters in this sea area. It should also be noted that the pure Ob waters in Ob Bay were found quite far south of the estuary of the bay. This is related to strong (>10 m/s) northern winds that preceded oceanographic works, which displaced Ob water inside the bay. Thus, the Ob and Yenisei waters had a local effect on the studied area in 2007 (results of the Cruise 54 of the R/V *Akademik Mstislav Keldysh*). It should be noted that the calculated contribution of melted ice in the indicated part of the sea is quite high, 20–30%. Since ice in the western part of the sea is preserved up to the beginning of August (data of Arctic and

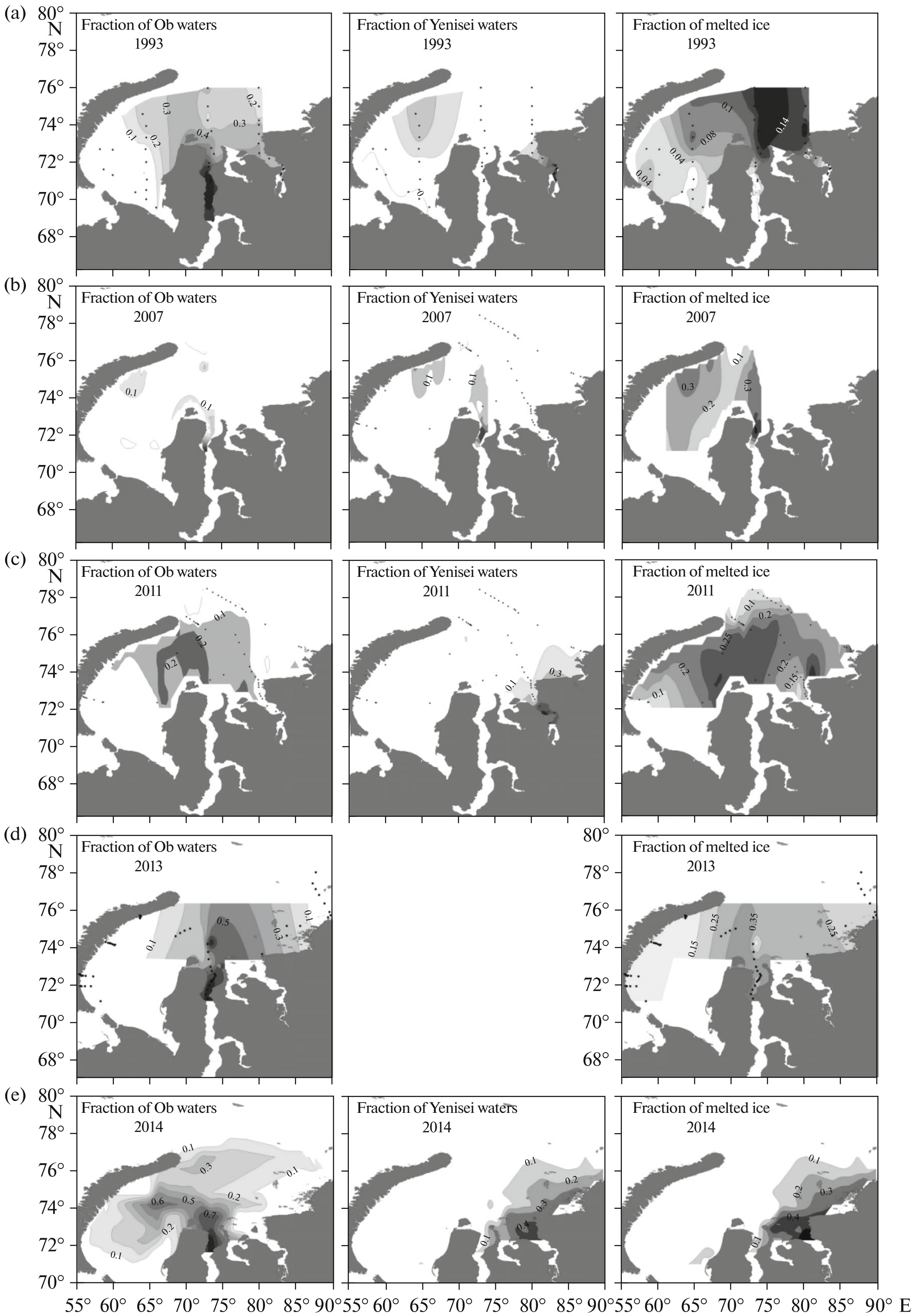

Fig. 8. Contributions of Yenisei and Ob waters, as well as melted ice (relative units), to formation of surface layer of Kara Sea using results of this work.

Antarctic Research Institute (ANII)), this calculation seems quite valid in combination with data on the weak wind force near the eastern coast of Novaya Zemlya during works. A quite high fraction of calculated melted ice in the estuary of Ob Bay is possibly related to the effect described in [29].

2011. A distinctive feature of river runoff in 2011 is the earlier and more intense flooding on the Yenisei compared to previous years (Fig. 2c). Analysis of air circulation above the sea surface (NCEP/NCAR reanalysis data) showed that a stable southern wind prevailed over the entire sea basin from beginning of works to mid-September. This wind transferred fresh water far to the north and east of the estuary of the bay. From mid-September, the wind changed direction to relatively weak northerly, and starting from the last ten days of September, the northern wind steadily affected the Ob–Yenisei coastal waters and to the north of them, bringing northern Kara Sea waters to this area.

Calculations showed that the fraction of Yenisei waters accounted for over 50% in the central and southern parts of the studied water area of Yenisei Bay (Fig. 8c), as well as in the relatively narrow coastal zone east of the bay along the coast of the Bezymennyi Peninsula. Such a distribution is very consistent with atmospheric circulation at that time. The content of Ob waters in the central part of the sea varied from 10 to 20%. The southwestern and northeastern parts of the sea also reveal the effect of Ob waters, but their fraction in surface waters is no more than 10%. Our conclusions are inconsistent with the previous view on the contribution from the Ob and Yenisei to the surface sea layer in autumn 2011 [6]. The cited authors concluded that Yenisei waters played a decisive role in desalination of the Kara Sea basin in 2011. Judging from the monthly discharge of Ob and Yenisei rivers in 2011, as well as arguments by P.O. Zav'yalov et al., this seems quite valid. In terms of distribution over the sea surface, Ob waters in 2011 prevailed over Yenisei waters due to the difference in their flood dates, as already mentioned above.

According to our calculations, the contribution of melted ice accounted for about 25% in the central part of the sea, near Ob Bay, and from 10 to 20% in the entire Ob–Yenisei coastal waters. Judging from data on the ice environment in the Kara Sea (ESIMO AARI), the sea basin is completely covered by ice from 30 to 200 cm thick for half a year and the area near the estuaries of Ob Bay and Yenisei Bay became completely free of ice only by the end of May. The wind reanalysis showed that from June to October, the central part of the sea, where the majority of ice accumulates, was in a relatively calm meteorological conditions. Correspondingly, the majority of melted ice water (based on rough estimates around 400 km^3 of fresh water) could remain in the indicated area. This can explain sufficiently high content of melted ice in the surface layer of the studied water basin in 2011.

2013. Judging from our calculations, the fraction of Yenisei waters during expedition studies seemed extremely low (therefore, the pattern with the contribution of Yenisei waters is not shown in Fig. 8d). Only one station from the Ob section yielded 17% of Yenisei waters, which presumably represented the residual Yenisei flood at the moment of sampling. At the same time, Ob waters accounted for 25–55%. It should be noted that the volume of discharged Yenisei waters is much lower than the average multiyear value for the flood period (80000 m^3/s), whereas the Ob water discharge during the flood time, like the hydrograph in general, is equivalent to the average multiyear values (Fig. 2d). Thus, the surface layer that gained a large volume of Yenisei waters became relatively homogenous in June at the moment of the work was performed. In July and August, the Ob discharge prevailed. Therefore, works that started in September revealed the presence of the large amount of Ob waters in the surface layer of the central Kara Sea on the basis of hydrochemical data.

The contribution of melted ice to the surface layer in 2013, like in 2011, was quite high, 30–35% in the central part of the sea, and decreased to 10% to the described above the boundaries of river runoff propagation. Such a strong effect of melted ice on the surface desalinated layer was caused by the ice environment at the end of 2012–first half of 2013 in combination with relatively low Yenisei River discharge. The entire Kara Sea basin remained covered by continuous annual ice (from 30 to 200 cm thick), which began to form in the second ten days of October up to the end of May. The entire basin was characterized by an ice concentration of seven-tenths by the end of June, and its southwestern and central parts became free of ice only by the end of July. It should be noted that Ob discharge at that moment was 1.5 times higher than Yenisei discharge and remained at the same level, whereas Yenisei discharge continued to decrease. Correspondingly, the great amount of Ob water, together with the remaining melted ice, was supplied to the surface layer by the beginning of expedition studies (beginning of September 2013), which was confirmed by calculations from the hydrochemical parameters, while the dynamic effect of the wind facilitated such propagation of river and other fresh waters.

2014. Based on our calculations, the fraction of Ob water in the lens reached 60% (or 0.6 arb. units in Fig. 8e). A small lens desalinated by the Ob waters with a salinity of 22–24 psu is also distinguished in the surface layer in the transect Ob Bay– Cape Zhelaniya, Novaya Zemlya. Such propagation of Ob waters is explained both by the quite large volume of fresh water supplied from the Ob River during the flood time (slightly above the average values for the river for that time, Fig. 2e) and wind action. Based on the reanalysis data, from the beginning of the work to the completion of the Ob transect (August 20, 2014), the northern winds predominating above the sea basin resulted in partial westward displacement of Ob water, which entered the central part of the sea due to flooding of the Ob. The freshwater flux in the surface layer in the bay was stopped by the same winds at 72° N; opposite direction of wind could have caused the northerly propagation of fresh Ob waters.

During the flood time (May–June), the water discharge in the Yenisei was around 60000 m^3/s (Fig. 2e), whereas the maximum flood level, on average, occurs in June when water discharge is 80000 m^3/s. At the same time, the average water discharge in May is 30000 m^3/s. In July, the Yenisei discharge is lower than the Ob discharge. Therefore, we did not find Yenisei waters in the central part of the sea. Exceptions were several stations in the northern part of Ob Bay, where over 20% of Yenisei waters were identified by calculations (Fig. 8e). This is possibly related to wind action. The reanalysis data indicate that the northern and eastern winds predominating up to August 20 could have partially transferred the lens desalinated by Yenisei water to the north of Ob Bay. After August 20, the wind changed direction to south and west, from 4–6 to 8–10 m/s, and the lens desalinated by the Yenisei runoff traveled eastward to the Taimyr coast. In the northern part of Yenisei Bay, the fraction of Yenisei waters at stations in August 22 accounted for around 50% despite the quite low water discharge.

The distribution of melted ice over the sea basin in 2014 is similar to that of Yenisei waters (Fig. 8e). Using AARI review ice maps, we established that the sea basin during the entire winter and spring was covered by annual ice over 30 cm thick, and the ice concentration in the offshore part of Yenisei Bay at the end of July was one-sixth. In addition, the two previous 10-day periods of August were dominated by northerly winds, which could have preserved ice and melted ice in the eastern coastal zone of Yenisei Bay. A further change in wind direction (as mentioned above) resulted in the eastward transfer of melted ice along the coast, together with Yenisei waters. During works performed in the indicated sea area three weeks later, the surface waters could have contained a great deal of melted ice. Calculation shows that the fraction of melted ice in the surface layer of the three southernmost stations in Yenisei Bay is 50%. The calculations also revealed a small amount of melted ice (around 10%) in the vicinity of the Yamal coast. This is presumably residual ice that accumulated in Baidaratskaya Bay: AARI data show an ice concentration of one-sixth in the bay as early as mid August, when works in the Kara Sea had already begun.

CONCLUSIONS

This work represents a continuation of study begun back in the 20th century by collaborators of the Laboratory of Biohydrochemistry of the Shirshov Institute of Oceanology, the Russian Academy of Sciences. The results of analysis and calculations based on natural observations provide information on the continental runoff distribution over the sea basin. It should be taken into account that, as compared to other World Ocean regions with powerful continental runoff, this problem for the Kara Sea is complicated by the presence of Siberia's two largest freshwater sources. It should be added that the analysis performed in this study involved all presently available techniques of sea and ocean studies, except for numerical simulation. This study has potential for the entire Arctic region.

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