MARINE CHEMISTRY

ORIGIN OF FRESHWATER COMPONENT IN ESTUARIES OF THE OB AND YENISEI RIVERS AND WATERS OF KARA SEA ADJACENT ZONES BASED ON ISOTOPIC (ΔD, Δ¹⁸O) DATA

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Received April 25, 2024

Revised June 03, 2024

Accepted October 03, 2024

Abstract. Methods of estimation the isotopic parameters (δD, $\delta^{18}O$) of the freshwater component in the river-sea transition zone are considered in this work. This research is based on samples collected at the end of the summer season along two meridional sections laying from the estuaries of the Ob and Yenisei rivers to the center of the Kara Sea. The runoff of these rivers has contrasting isotopic parameters contrasting ($\delta^{18}O = -15.0 \pm 0.3$‰, $\delta D = -112.7 \pm 2.1$‰ for the Ob and $\delta^{18}O = -18.9 \pm 0.6$‰, $\delta D = -142.2 \pm 4.3$‰ for the Yenisei). It has been established that river waters located within the surface layer of sea water do not have time to homogenize: in the center of the Ob-Yenisei plume, the part of Ob waters is 60%. Within river estuaries, FC is homogeneous only in the upper layer of water (less than 5 m); with depth, variations in $\delta^{18}O$(FC) values reach 16‰ for the Ob Bay and 12‰ for the Yenisei Bay, exceeding the annual course of seasonal variations of this value in river water. In the bottom layer for the estuarine zones of both rivers, the presence of a total FC with light isotopic characteristics corresponding to regional atmospheric precipitation is observed, that FC is supplied to the estuary zone with the waters of the Kara Sea.

Keywords: *oxygen and hydrogen isotopes, river runoff, the Kara Sea, fresh component*

DOI: 10.31857/S00301574250105e3

INTRODUCTION

Freshwater runoff from the continents is not only an indicator of climatic changes, the spread of anthropogenic pollution and deposition of terrigenous material in the continental shelf zone [13, 23, 25, 30], but also affects the biological, geochemical and physical parameters of the waters of the Arctic seas. One of them is the Kara Sea, a highly desalinated sea basin [4, 8, 9], into which two large Siberian rivers, the Ob and the Yenisei, flow, which supply the Arctic shelf with about a quarter of the total continental runoff in the Eastern Arctic [15, 29]. Together with other sources of fresh water – atmospheric precipitation or melt water from sea or river ice – river runoff forms the so-called total freshwater component (TFC) of the Kara Sea. The main feature of the PC of the Kara Sea is difference in isotopic parameters of the two main sources of river water – the Ob and the Yenisei. This difference is due to the fact that isotopic parameters of river runoff predominantly inherit information on the contribution of precipitation and groundwater to the river water balance [18, 31] over the entire catchment area. The Ob and Yenisei catchments occupy large areas extending both in meridional and latitudinal directions, occupying different climatic zones, which leads to the discharge of two large rivers with contrasting isotopic ($\delta^{18}O$, δD) water characteristics into one sea basin (Fig. 1).

The works forming an idea of isotopic parameters of river runoff into the Kara Sea are few in number and mainly consider the oxygen isotope system, while estimates of hydrogen isotope composition are practically not found in the literature. Table 1 systematizes the main data on isotopic parameters ($\delta^{18}O$, δD) of Ob and Yenisei waters obtained both in the river-sea transition zone [1, 4, 8, 9] and in areas located directly in river estuaries [11, 20]. Despite the fact that there are significantly more published data on the oxygen isotope composition ($\delta^{18}O$), they are not always reproduced in the works of different authors.

Fig. 1. Areas of the Ob (I) and Yenisei (II) catchment areas, according to ArcticGRO data [16].

Our preliminary estimates of isotopic parameters of Ob and Yenisei waters in the river-sea transition zone [4] also require refinement, since a bimodal distribution of $\delta^{18}O$ and δD values was obtained for Yenisei waters, which for one of the stations turned out to be close to Ob waters (Table 1). The possibility of the appearance in the Yenisei Bay of Kara Sea waters desalinated by the Ob runoff has been discussed earlier [25, 26], but this observation needs confirmation.

The lack of systematic information on isotopic parameters of river runoff into the Kara Sea and the inconsistency of published data determined the objectives of the present work, which consist in testing different approaches to estimating isotopic parameters (δD, $\delta^{18}O$) of the Ob and Yenisei runoff and establishing their averaged values suitable for model estimates. We pay special attention to the role of river water and other desalination agents in the formation of PC isotopic characteristics in the river-sea transition zone. The solution of these problems on the example of the Ob and Yenisei complements the existing ideas about the distribution of desalination components within the Arctic water areas.

MATERIALS AND METHODS

The research material was collected during the 66th cruise of the R/V "Akademik Mstislav Keldysh" (2016) using Niskin bathometers of the oceanographic probe SBE 911 with the Rosette 32 complex. Desalinated seawater samples were collected at the stations located along two meridional transects extending from river estuaries to the center of the Kara Sea. The length of the Ob transect was 453 km and the length of the Yenisei transect was 472 km (Fig. 2). Oxygen isotope

Table 1. Published estimates of isotopic parameters of Ob and Yenisei waters

Source	Selection period	Method estimation*	Number of data	δD, ‰	$\delta^{18}O$, ‰
		Ob			
Bauch et al., 2005 [8]	2000 (Aug-Sept.)	1	n/a	–	–16.1
	2001 (Aug-Sept)	1	n/a	–	–15.7
Bauch et al., 2003 [9]	1999 (Aug-Sept)	1	34	–	–16.8
Brezgunov et al., 1980 [1]	1976 (Jul-Aug)	2	8	–	–16.4
	1977 (Jul-Aug)	2	5	–	–16.1
	1977 (March)	2	11	–	–14.6
Cooper et al., 2008 [11]	2003–2006	3	17	–	–14.9
Dubinina et al., 2017 [4]	2014 (Aug-Sept)	4	1	–131.4	–17.6
		Yenisei			
Bauch et al., 2005 [8]	2000 (Aug-Sept)	1	n/a	–	–17.0
	2001(Aug-Sept)	1	n/a	–	–17.0
Bauch et al., 2003 [9]	1999 (Aug-Sept)	1	10	–	–18.1
Cooper et al., 2008 [11]	2003–2006	3	17	–	–18.4
Dubinina et al., 2017 [4]	2014 (Aug-Sept)	4	2	–134.4 –120.7	–17.7 –15.8

*1 – Linear extrapolation of data to S = 0; 2 – averaging of results of direct measurements of $\delta^{18}O$ values in estuarine water samples with S < 1‰; 3 – weighted averages of $\delta^{18}O$ values in fresh water at river stations; 4 – results of direct measurements of $\delta^{18}O$ values in estuarine water samples.

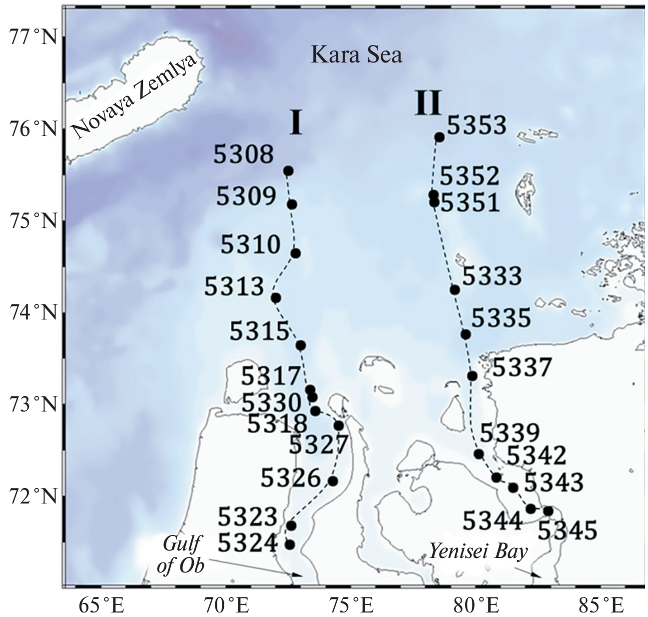

Fig. 2. Location of the studied transects in the Kara Sea (66th voyage of the R/V "Akademik Mstislav Keldysh"). I – Ob section; II – Yenisei section.

analysis of the samples was performed by isotopic equilibration in CF-IRMS mode using a DELTA V+ mass spectrometer and GasBench II option. Hydrogen isotope analysis was performed in DI IRMS mode on a DELTAplus mass spectrometer (Thermo, Germany) after decomposition of water microsamples on hot chromium (H/Device). All $\delta^{18}O$ and δD values were calibrated in the "V-SMOW-V-SLAP" scale and determined with an accuracy of ±0.05 and ±0.3‰, respectively.

RESULTS

The spatial distribution of isotopic (δD and $\delta^{18}O$) data and salinity of the Ob and Yenisei sections are shown in Fig. 3. 3. The observed salinity distribution indicates that the waters of the studied sections are desalinated relative to waters of Atlantic origin (for the North Atlantic $S = 34.9$ PSU according to [3, 4]) at all depths and along the entire length of the studied sections. As would be expected, maximum desalination is manifested in the surface layer, where salinity values reach their minimum values (5 PSU or less). A simple estimate of the freshwater component (X_{PC}) in the studied samples can be obtained from the salinity balance:

$$X_{PC} = \frac{S_{Atlantic} - S_{sample}}{S_{Atlantic}}, \qquad (1)$$

where $S_{Atlantic}$ is the salinity of waters of Atlantic origin entering the Kara Sea from the Barents Sea (34.9 PSU, according to [3, 4]); S_{sample} is the salinity of the sample. Estimates from equation (1) exceed 90% in the zone of river estuaries and fall to 1% and less in the bottom waters of the central part of the studied sections.

The isotopic parameters δD and $\delta^{18}O$ (Fig. 3), being conservative tracers, are distributed in space similarly to salinity [12]. The maximum values of δD and $\delta^{18}O$ values on the Ob meridional transect were 0.0 and −2.1‰, respectively, in bottom waters (175 m) at station 5308, maximally distant from the mouth of the Gulf of Ob. In the Yenisei Gulf, the maximum values of δD and $\delta^{18}O$ values are also observed in bottom waters (60 m) at station 5353, maximally remote from the river mouth and comprise –0.4 and –3.3‰, respectively, at a salinity of 33.74 PSU In the Yenisei Bay, the maximum values of δD and $\delta^{18}O$ are also observed in bottom waters (60 m) at station 5353, maximally remote from the river mouth and comprise –0.4 and –3.3‰, respectively, at a salinity of 33.74 PSU.

The minimum values of δD and $\delta^{18}O$ and salinity were obtained for the surface layer water at the stations in the southernmost parts of the studied sections. Stations 5323, 5324, 5326, 5327 are located directly in the Gulf of Ob, at some stations (stations 5323, 5324) the sea depth does not exceed 15 meters and the range of observed salinity values is from 0.17 PSU near the surface to 31.10 PSU in the bottom layer of the stratum. The δD and $\delta^{18}O$ values also vary with depth and the lowest values are characteristic of the surface layer waters: δD and $\delta^{18}O$ values (station 5323) are −115.1‰ and −15.6‰, respectively. Stations 5342, 5343, 5344, 5345 located in the Yenisei Bay are also characterized by the minimum values of δD and $\delta^{18}O$ values obtained for surface waters (station 5342), they comprise −148.1‰ and −19.9‰, respectively. The greatest depth in this area reaches 19 meters (station 5345), and the salinity range is from 0.44 to 31.97 PSU.

DISCUSSION OF RESULTS

Estimation of isotopic parameters of river runoff

From the diagrams presented in Fig. 3, it follows that most of the PC is concentrated in the surface water layer, forming the so-called river plume regularly observed in the Kara Sea [21, 26, 28]. The waters of the Ob and Yenisei spread over the sea surface, gradually mixing with the underlying sea waters. This allows us to consider the waters of the Kara Sea in the zone of river plume propagation from the position of mixing of Atlantic waters coming from the Barents Sea with river runoff waters, mainly of the Ob and Yenisei [4, 8, 29]. The two-component mixing

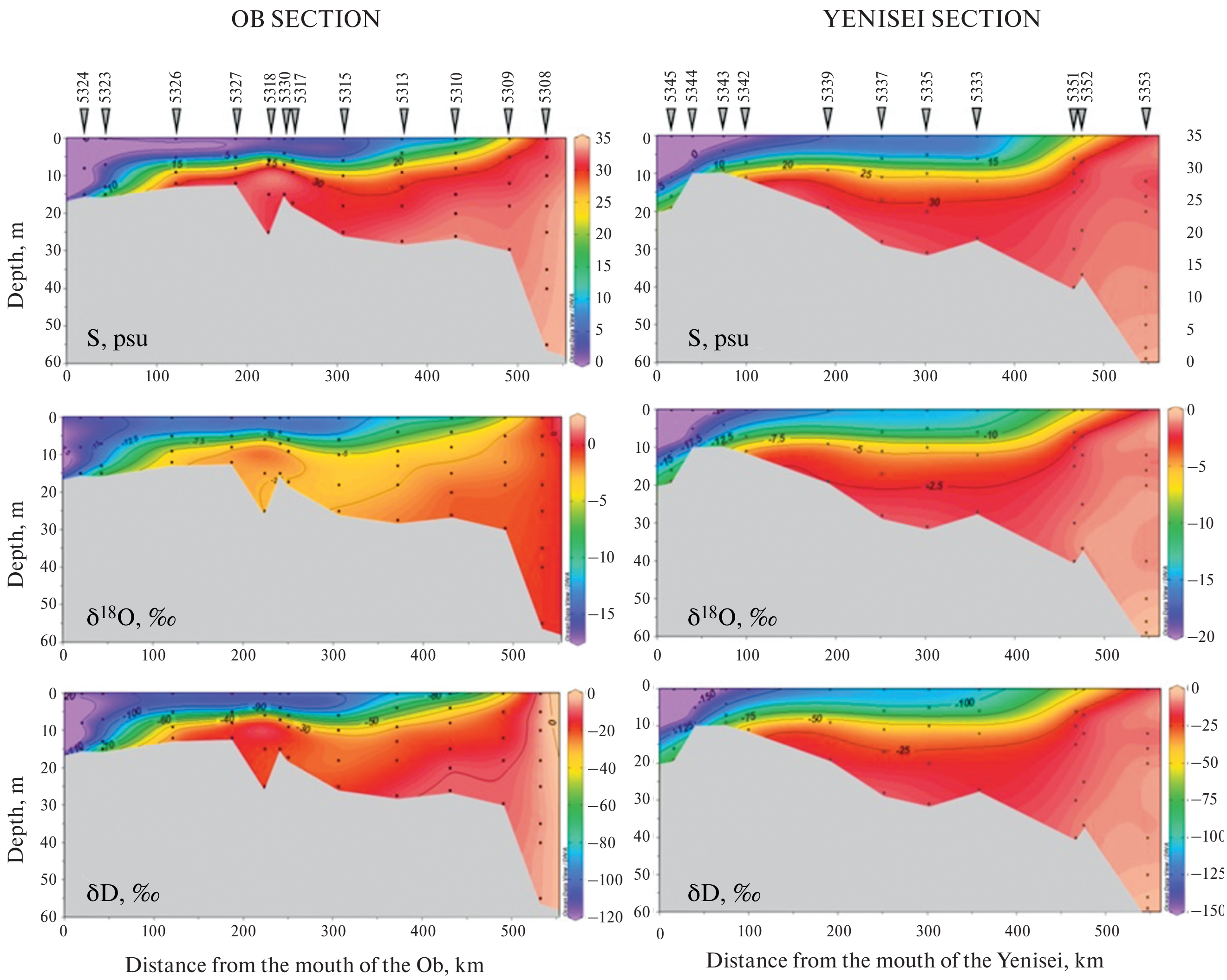

Fig. 3. Spatial distribution of salinity (S) and isotopic parameters ($\delta^{18}O$, δD) in waters of the Ob (A, B, C) and Yenisei (D, D, E) sections.

is described by a linear equation in the coordinates "isotopic composition-salinity", or δ-S [1, 8, 10]. The free term of the linear equation will be close to the $\delta^{18}O$ or δD values of the total freshwater component, which in the river plume zone is represented predominantly by river water. The δ-S coupling equations and their statistical characteristics obtained for the waters of the Ob and Yenisei sections are given in Table 2. The values of the free term in these equations are presented as averaged river flow parameters in Table 3. Despite the high correlation coefficients given in Table 2, Fig. 4 shows that there is no strict linear relationship between isotopic parameters and salinity in the waters of the studied sections. The distribution of points on the diagrams of this Fig. indicates deviation from the model of simple two-component mixing and more resembles a third degree polynomial with a kink in the region of salinity 10–25 PSU. This situation probably reflects the formation of PC due to mixing of river waters of the Ob and Yenisei, different in their isotopic parameters. As an additional factor, one can note the possible influence of the contribution of melt water from sea or river ice, which can persist in the surface desalinized layer until the end of July [5, 9, 17, 24].

Table 2. Relationship equations between isotopic characteristics and salinity for waters of the Ob and Yenisei sections

Ob transect (n= 61)	**R^2**
$\delta^{18}O = 0.41(\pm0.01)$ S-14.77($\pm$0.16)	0.99
$\delta D = 3.09(\pm0.04)$ S-111.53($\pm$1.12)	0.99
Yenisei transect (n=53)	
$\delta^{18}O = 0.53(\pm0.01)$ S-18.64($\pm$0.53)	0.98
$\delta D = 3.98(\pm0.09)$ S-140.52($\pm$2.13)	0.98

Table 3. Isotopic parameters of river water entering the Kara Sea

№	Method evaluation method	parameter, ‰	Ob		Yenisei	
				n		n
1	Extrapolation to S = 0 of all section data	$\delta^{18}O$	−14.8 ± 0.2	61	−18.6 ± 0.5	53
		δD	−111.5 ± 1.1		−140.5 ± 2.1	
2	Calculation according to (1, 2) with geographical exclusion	$\delta^{18}O$	−15.3 ± 0.4	6	−19.5 ± 0.7	7
		δD	−114.7 ± 1.6		−146.9 ± 4.7	
3	Calculation according to (1, 2) with formal exclusion	$\delta^{18}O$	−14.8 ± 0.7	19	−18.5 ± 1.2	18
		δD	−112.0 ± 4.8		−139.2 ± 9.2	
Medium:		$\delta^{18}O$	−15.0 ± 0.3		−18.9 ± 0.6	
		δD	−112.7 ± 2.1		−142.2 ± 4.3	

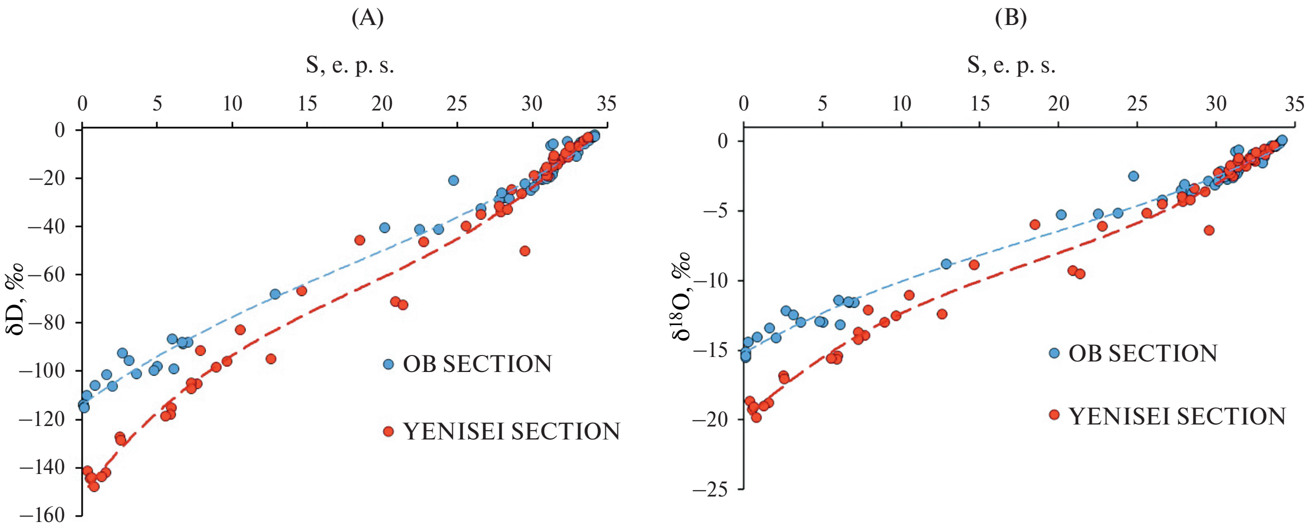

Fig. 4. Relationship between salinity and isotopic composition of hydrogen (A) and oxygen (B) in waters of the studied sections.

In the region of minimum salinity in diagrams of Fig. 4, the values of $\delta^{18}O$ and δD are close to the values of the free term in the statistical equations from Table 2. However, the small scatter of data in the minimum salinity region, noticeable in the diagrams of Fig. 4 shows that even in the zone of river runoff dominance, the contribution of other desalinization sources to PC cannot be completely excluded [2, 6]. For this reason, the values of δD and $\delta^{18}O$ obtained by extrapolating all data obtained for transects or individual stations to zero salinity can be used to estimate river discharge parameters, but with great caution. Our estimates of $\delta^{18}O$ and δD values of river runoff of the Ob and Yenisei obtained by this method are given in Table 3 (Method 1).

In addition to extrapolation to zero salinity, a material balance equation linking isotopic parameters and the quantitative ratio of fresh and saline waters in each sample studied can be used [7, 9, 27]:

$$\delta_{PC} = \delta^0 - \frac{\delta^0 - \delta_{>I@}}{X_{PC}}, \quad (2)$$

where X_{PC} is the fraction of the fresh component in the sample calculated from the salinity balance (1), δ_{PC} is the isotopic composition of oxygen or hydrogen of the fresh component, δ^0 is the isotopic composition of oxygen or hydrogen of the initial seawater. In calculations, its parameters determined for waters of Atlantic origin circulating in the Barents Sea δD = 1.56±0.40‰; $\delta^{18}O$ = 0.25± 0.1‰ [3, 4] are adopted.

Application of equation (2) to slightly desalinated waters (with X_{PC} less than 10%) leads to high error and unrealistic estimates of $\delta^{18}O$ and δD in the freshwater component. Such samples should be excluded from the calculations and the remaining data should be analyzed, grouping them by geographical or formal (mathematical) principle. In the first case, we assume

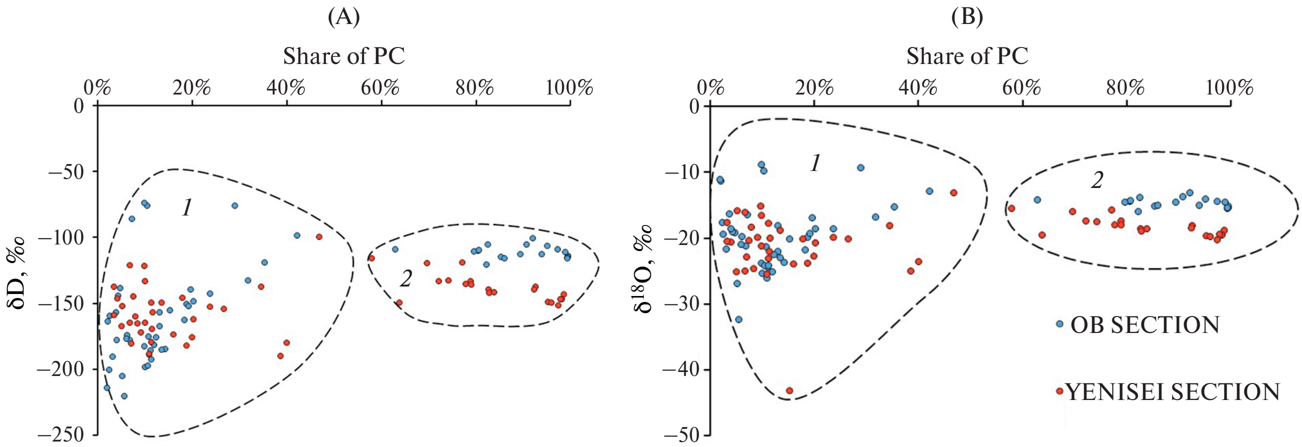

Fig. 5. Dependence of δD (A) and $\delta^{18}O$ (B) values of the freshwater component on its content in waters of the Ob and Yenisei sections. Dotted areas are waters with PC content less than 60% (I) and more than 60% (II).

that in the southernmost (estuarine) parts of the transects, the contribution of any other freshwater sources other than the waters of a particular river is negligible. Isotopic parameters of river waters of the Ob and Yenisei obtained in this way are given in Table 3 (Method 2).

The criterion for the suitability of the data on a formal basis is the absence of dependence of the δD and $\delta^{18}O$ values of the fresh component on its content in the sample, calculated by equations (1, 2). In Fig. 5, all calculated values of δD and $\delta^{18}O$ of PC form two groups of values: group (I) includes waters with PC content less than 60%, and group (II) includes waters containing more than 60% PC. It can be seen that waters of the first group have a wide range of variations of δD and $\delta^{18}O$ PC values, and the second group is characterized by minimal variations of δD and $\delta^{18}O$ PC values (Fig. 5). Significant variations of PC isotopic parameters indicate the presence of fresh waters with different isotopic characteristics, which are manifested against the background of the absence of dominance of one of PC sources, in this case, river water. In the samples of the second group, the variations of PC isotopic parameters are minimal, and this is due to the predominance of river water over the other sources of desalination. Thus, we can assume that the points of the second group represent the characteristics of the corresponding river waters: Ob for the Ob section, and Yenisei for the Yenisei section. The averaged values of these estimates of δD and $\delta^{18}O$ PC, are given in Table 3 (Method 3).

River water distribution in the Ob-Yenisei plume

The mean estimates of isotopic parameters of the Ob and Yenisei river discharge at the time of observations (Table 3) can be used as reference values δD and $\delta^{18}O$ that allow us to identify the discharge of each river. We applied these values to assess the preservation of the isotopic signal of the Ob and Yenisei waters within a single river plume forming in the Kara Sea outside the estuarine zones of these rivers. The river runoff entering the Kara Sea spreads mainly in the northern and northeastern direction in the form of plumes that mix poorly with the underlying sea water [21, 28, 29]. In the central part of the Kara Sea, the Ob and Yenisei plumes merge into the so-called Ob-Yenisei common river plume [21, 25, 28]. According to some estimates, the central part of this plume is thought to be dominated by Ob River water [26], although there are no precise estimates of the Ob and Yenisei water content in the common plume. We calculated the contribution of water from each river based on the assumption that the PC in the Ob-Yenisei plume zone consists mainly of Ob and Yenisei waters. The calculation was carried out for samples taken within the surface layer (0–16m), which is partially represented by the waters of the river plume [26]. The salinity of these waters does not exceed 21 PSU, and the PC fraction reaches 60%. The calculation results are shown in Fig. 6 in the form of spatial distribution within the plume of the Ob water share in the PC composition (accordingly, the distribution pattern of Yenisei water will be reversed, since a two-component PC composition was assumed).

According to the calculation, the share of Ob water in the PC composition of the Ob-Yenisei plume increases gradually, reaching 60% at stations 5333 and 5351, which are more than 350 km away from the beginning of the Yenisei section. Thus, it can be stated that within the Yenisei section, the predominance

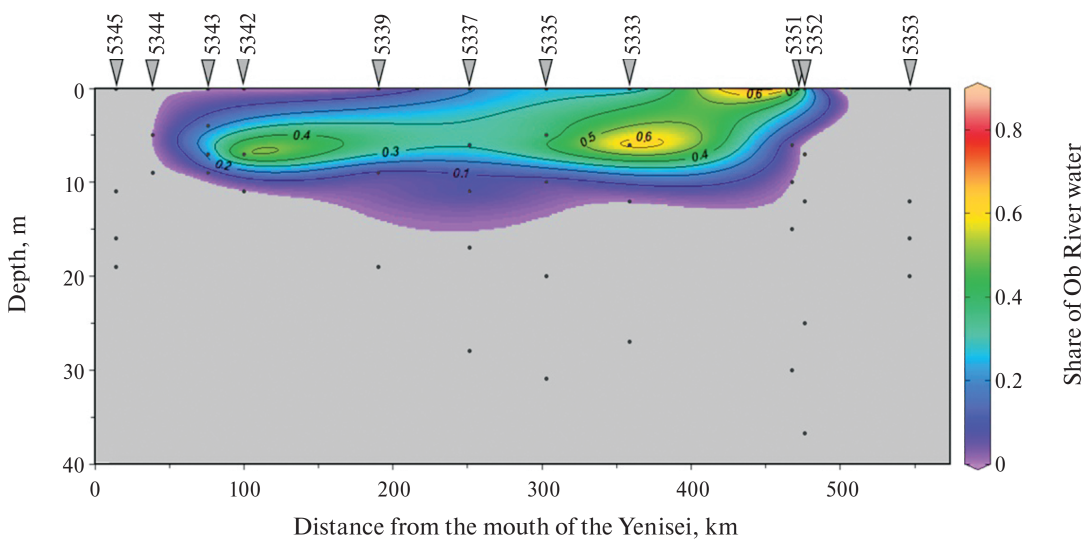

Fig. 6. Proportion of Ob River water in the PC composition of the Ob-Yenisei plume in the zone of its intersection with the Yenisei section.

of the Ob waters over the Yenisei waters is indeed observed, and the character of the distribution of the Ob waters within the plume shows that the waters coming out of the Gulf of Ob cross the trajectory of the Yenisei plume, overlapping it. At the same time, the isotopic labels of water from both rivers remain preserved, indicating the heterogeneous state of the PC within a single plume.

Distribution of PC isotopic characteristics with depth

According to the obtained estimates of $\delta^{18}O$ and δD values in the fresh component of slightly desalinated waters of both sections (region I in Fig. 5), its isotopic parameters are nonhomogeneous, which suggests that not only river water but also other fresh waters are involved in the mixing processes in the Kara Sea. This is most clearly manifested when considering the waters of the stations located within the estuarine zones of each of the rivers. Fig. 7 (a, b) shows the values of $\delta^{18}O$(PC) calculated from equation (2) as a function of sampling depth for the Gulf of Ob and Yenisei Bay (the distribution pattern of δD(PC) values looks similar). For both rivers, a relatively homogeneous PC state is observed in samples taken from the surface layer, which is probably provided by mixing of river water by currents and wind loading. At depths greater than 5 m, there is a significant scatter of $\delta^{18}O$(PC) values, which cannot be explained by calculation

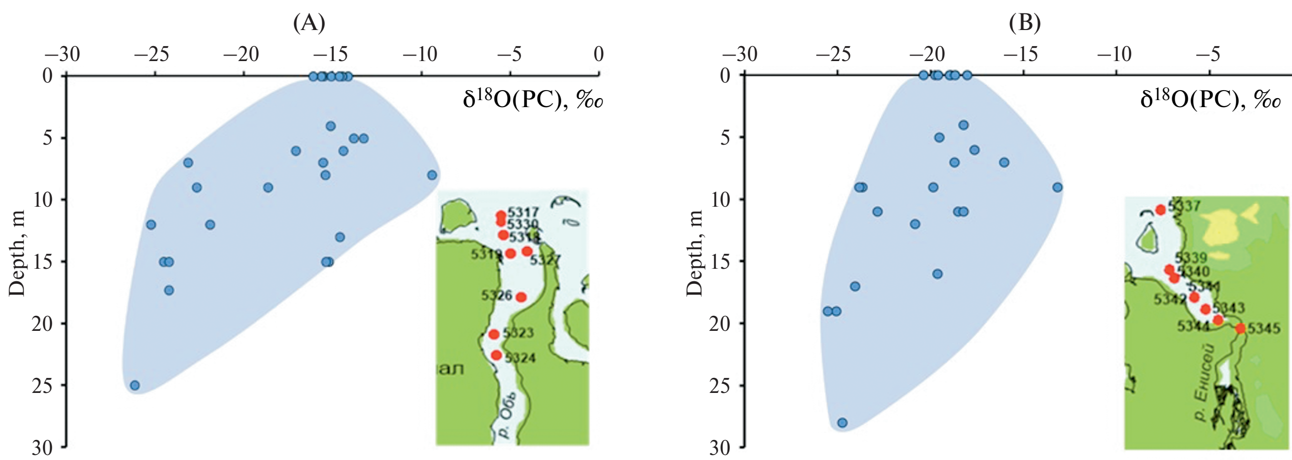

Fig. 7. Distribution of calculated $\delta^{18}O$ values of the freshwater component (PC) as a function of depth: (A) – Gulf of Ob, (B) – Yenisei Bay. The dotted line limits the interval of variations of $\delta^{18}O$ values of river water at the ArcticGRO observation stations [16] for the period from September 2015 to August 2016, which covers the annual interval preceding the sampling. The maps show the southern sections of the studied transects located within the Gulf of Ob (A) and Yenisei Bay (B).

errors, since all these samples are mainly characterized by low salinity (from 0.17 to 6.72 PSU in the waters of the Gulf of Ob and from 0.44 to 12.64 PSU in the Yenisei Bay).

In the near-bottom horizons, especially at the outlet of the estuarine zone, salinity increases to 22.56–31.22 PSU in the Gulf of Ob and to 18.54–31.97 PSU in Yenisei Bay. Since even these salinity values are not capable of leading to erroneous estimates of the PC isotopic parameters, the observed depth distribution of $\delta^{18}O$(PC) and δD(PC) values is not an artifact and should have an explanation.

It makes sense to compare the obtained estimates of PC isotopic parameters with the interval of seasonal variations of river waters. For this purpose, we plotted in Figs. 7a and 7b the intervals of seasonal variations of $\delta^{18}O$ values in Ob and Yenisei waters from the open database of the ArcticGRO project [16]. We used the observational data obtained for the period of one year preceding the time of sampling, i.e., from September 2015 to August 2016 inclusive. The obtained intervals of seasonal variations for river water describe the data for the surface layer only (Fig. 7). The PC composition at depths greater than 5 m is clearly heterogeneous – $\delta^{18}O$(PC) values have a significant scatter and show a slight downward trend with increasing depth. The general interval of $\delta^{18}O$(PC) values at depths greater than 5 m, both in the Gulf of Ob and in the Yenisei Bay, is significantly wider than the annual variations of this parameter in river water. This means that the fresh component contained in the waters of deeper horizons is obviously not only of river origin.

The spatial distribution of $\delta^{18}O$(PC) values shows (Fig. 8) that the isotopically lightened freshwater component is confined to the bottom layer and enters the Ob Bay and Yenisei Bay from the Kara Sea. The $\delta^{18}O$ values of about -20...-25‰ correspond to the composition of atmospheric precipitation at high latitudes, which partially desalinate the waters of the Kara Sea [2], as well as to the average composition of the atmospheric component in the Arctic –23 ‰ [14]. The higher values of $\delta^{18}O$(PC) observed at horizons of about 10 m may result from the contribution of melted ice, which is enriched in the ^{18}O isotope in equilibrium with water by a value of about 2 ‰ [19, 22].

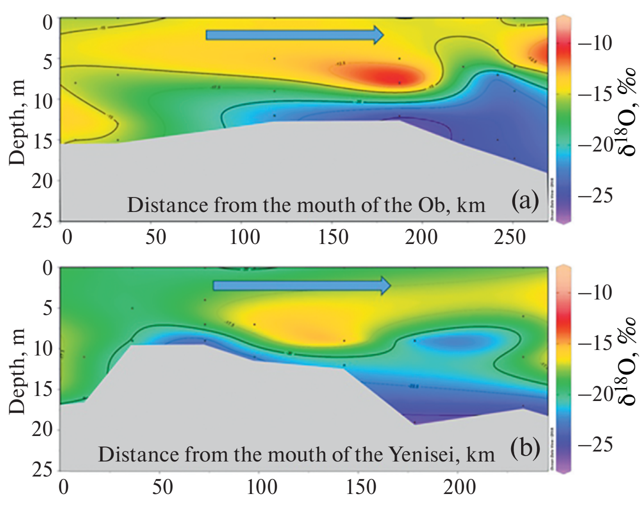

Fig. 8. Distribution of $\delta^{18}O$(PC) in the waters of the Gulf of Ob (A) and Yenisei Bay (B). The arrows indicate the direction of river flow.

The freshwater component of predominantly river origin is preserved mainly in the surface water layer of estuaries, inheriting the spectrum of variations in isotopic parameters of river water of previous seasons. However, this does not affect the fundamental correlation between the isotopic characteristics of the two rivers' runoff: the Ob surface water is characterized by higher values of $\delta^{18}O$ (≈ –15‰) than the Yenisei (≈ –18...–20‰). The Ob Bay is also characterized by the presence of water lenses with elevated $\delta^{18}O$ values of the fresh component, apparently represented by melted river ice. For the waters of the Yenisei Gulf, the presence of water interlayers with elevated $\delta^{18}O$(PC) values is weaker, and may be associated not only with the presence of melt water from river ice, but also with the inflow of water desalinated in the Gulf of Ob into the Yenisei Gulf, which was noted earlier [25].

CONCLUSION

The results presented in this paper are based on materials from a single cruise collected during one summer season. Consequently, seasonal variations remain beyond the scope of the discussion, which was not the purpose of this paper. We have tried to show that in such a complex basin as the Kara Sea, even in a zone dominated by river runoff (e.g., directly in river estuarine zones), desalination cannot always be considered as a process of two-component mixing of sea and river water. This is also evidenced by the non-homogeneous distribution of river water within the Ob-Yenisei plume. For example, in the central part of the Yenisei section crossing the Ob-Yenisei plume, the PC is represented by a mixture of 60% Ob and 40% Yenisei waters.

Comparison of the obtained estimates of $\delta^{18}O$(PC) with seasonal variations of $\delta^{18}O$ and δD values in river waters shows that the river water column in the estuarine zone can hardly be considered homogeneous with respect to PC isotopic parameters. This is very clearly demonstrated by the example of the vertical

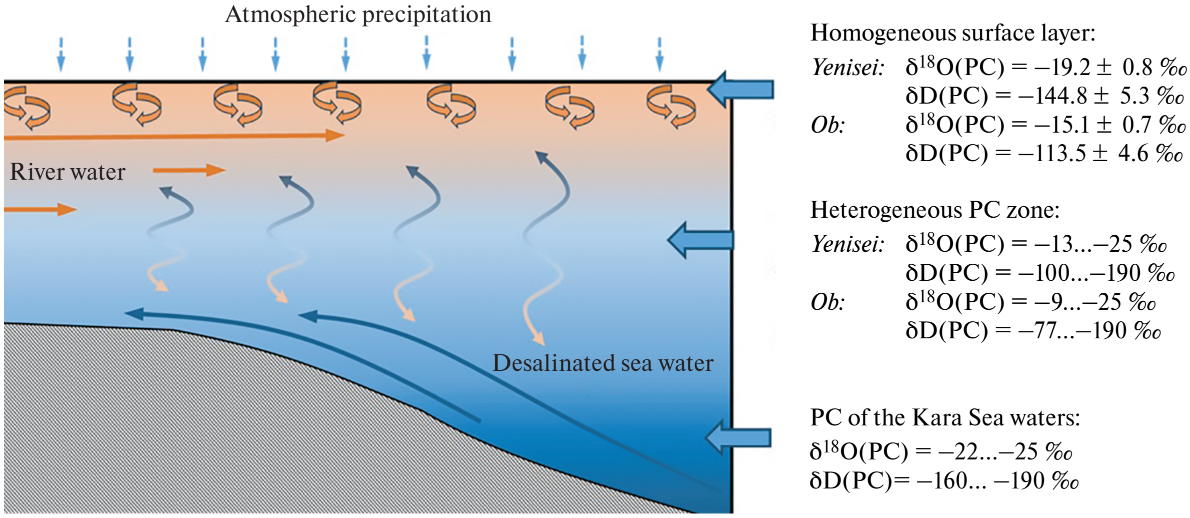

Fig. 9. Characterization of freshwater components in the river-sea transition zone on the example of the Gulf of Ob and Yenisei Bay at the end of July 2016.

distribution of $\delta^{18}O$(PC) values (and δD(PC), which behave similarly) within the Yenisei Bay and the Gulf of Ob. In estuarine zones, it would be logical to expect a sharp predominance of water from the corresponding river in the PC composition, but our data show that this is not the case, and that within the estuaries of large rivers one can detect a freshwater component of extraneous, non-river origin, brought from the sea. As we were able to show, the entire water column in both the Gulf of Ob and the Yenisei Bay turns out to be heterogeneous in terms of the composition and origin of the freshwater component. Its distribution and main ways of spreading in the river-sea transition zone at the time of research (late July) can be represented by the formal scheme shown in Fig. 9.

In the surface layer of the river estuary (less than 5–10 m), the fresh component is formed predominantly by river runoff water, possibly with a small participation of local precipitation and melted river ice. As it was established, in the upper horizons of both the Gulf of Ob and Yenisei Bay waters, these components have time to homogenize, representing some unified characteristics of "river runoff". Equally homogeneous is the freshwater component contained in the waters entering the zone of both estuaries from the Kara Sea. This PC has isotope-light characteristics ($\delta^{18}O \approx -22 \ldots -25$‰, $\delta D \approx -160 \ldots -190$‰), formed due to the contribution of atmospheric precipitation from high latitudes, and its homogeneity is explained by the long residence time of this type of PC in the Kara Sea waters. Seawater clarified by this component forms the near-bottom layer, which is gradually wedged out as one moves away from the mouth of a bay or lip. The waters between the surface and bottom layers are heterogeneous with respect to PC isotopic characteristics, apparently due to more intense lateral mixing of waters in the estuary compared to the rate of vertical mixing. The spread of values of $\delta^{18}O$(PC) in the intermediate layer reaches 16‰ in the Gulf of Ob and about 12‰ in the Yenisei Bay, which is beyond the margin of error of any estimates for river waters, including consideration of seasonal variations. Such strong changes are probably related not only to the mixing of isotope-light "Karskomorsky" PC and river water, but also to the presence of additional components, for example, melted river ice in the Gulf of Ob or the inflow of water desalinized in the Gulf of Ob into the northern part of the Yenisei Bay.

ACKNOWLEDGEMENTS

The authors are deeply grateful to the scientific leader of the cruise, Academician of the Russian Academy of Sciences M. V. Flint, and thank G. I. Nadyarnykh and the team of hydrophysicists led by S. A. Shchuka for the hydrophysical data provided.

FUNDING

The work was performed within the framework of the state assignment of IGEM RAS, topic FMMN-2024-0021 124022400138-5, hydrogen isotope analysis and interpretation of the obtained data was supported by RNF grant No. 23-17-00001.

CONFLICT OF INTERESTS

The authors of this paper declare that they have no conflicts of interests.

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