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Sources and Mechanisms of Seawater Freshening in Tsivolky and Sedov Bays (Novaya Zemlya Archipelago) Based on Isotope Data (δD and $\delta^{18}O$)

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Abstract—Three-year monitoring (2014–2016) of isotope parameters (δD and $\delta^{18}O$) of water in Sedov and Tsivolky bays (Novaya Zemlya Archipelago) freshened by water of different origin (continental river runoff, atmospheric precipitation, and water supplied from the archipelago) showed that the degrees of freshening and sources of fresh water components were different for water located at different depths. The variability of the δD and $\delta^{18}O$ values was characteristic only of surface layer water containing up to 30% freshwater component. In 2015, surface water of Sedov Bay contained Ob River water, whereas water supplied from Novaya Zemlya predominated in Tsivolky Bay. The deep water of both bays showed evidence of freshening by high-latitude atmospheric precipitation. This water might have been transported via the St. Anna and Voronin troughs. The difference in freshening mechanisms of water in Sedov and Tsivolky bays was determined by the different seafloor morphologies and degrees of free exchange with Kara Sea water.

Keywords: oxygen and hydrogen isotopes, bays of the Novaya Zemlya, water desalination, Kara Sea, continental runoff

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INTRODUCTION

The Kara Sea, bordered in the northwest by Novaya Zemlya Archipelago, is the most freshened basin compared to other Russian Arctic seas. According to the earliest evaluations, about 40% of sea surface water is considered to be affected by freshening processes [24]. In addition to the common component for the Arctic region, the global freshwater source in the Kara Sea is the runoff from two great rivers—the Ob and Yenisei—which annually supply over 1500 km^3 of fresh water [18]. The abrupt seasonal discharge of river water causes freshwater plumes on the Kara Sea surface. Numerous studies, including those using isotope techniques, found that the river water mainly propagated within the upper layer of seawater (depths of 5–15 m or shallower) [1, 2, 9]. The main role in river water propagation throughout the water area of the Kara Sea is played by wind transfer, characterized by steady directions and capable of transporting freshened water to far distances, e.g., to the southeast coasts of the Novaya Zemlya Archipelago [3]. However, it is difficult to identify river water in coastal areas of the archipelago due to the occurrence of local freshwater (small seasonal streams and meltwater from glaciers).

The aim of the present study is to evaluate the roles of different global and local fresh water sources representing the evolutionary history and origin of natural water in the bays of the southeastern coasts of the Novaya Zemlya Archipelago using oxygen and hydrogen isotope geochemistry [8, 13, 15, 23, 25]. Sedov and Tsivolky bays are located relatively close to each other on the eastern coasts of the Novaya Zemlya Archipelago. However, the bays differ in depths, seafloor morphology, and degrees of openness with respect to the water area of the Kara Sea. The samples for research were collected over three years (2014–2016), which made it possible to evaluate the temporal stability of the isotope parameters of fresh water sources along with the degree to which these sources are involved in freshning the water areas of these bays.

It was found earlier that the central Kara Sea was characterized by two-component mixing of modified Atlantic water supplied from the Barents Sea and Ob and Yenisei estuarine water [1, 2]. However, with distance from continental runoff sources, runoff from the archipelago is involved in freshening processes, causing the isotope and salinity parameters to diverge from the simple two-component mixing model [2, 4]. Despite good knowledge of the isotope parameters in Kara Sea water [1, 2, 12], no special isotope studies

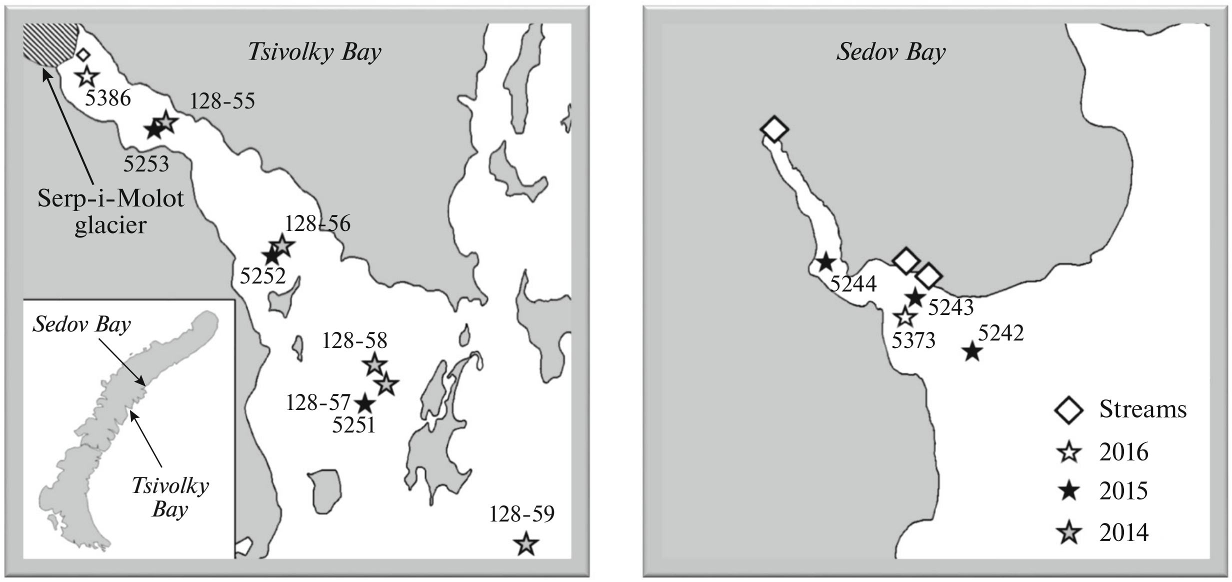

Fig. 1. Location of stations in bays of Novaya Zemlya Archipelago.

had been carried out earlier in the bays of the Novaya Zemlya Archipelago.

DESCRIPTION OF THE BAYS

Figure 1 shows the location of stations in the bays and local freshwater sampling sites. Tsivolky and Sedov bays are situated on the southeastern coast of Severny Island of the Novaya Zemlya Archipelago 45 km from each other. Tsivolky Bay lies to the southwest of Sedov Bay and cuts into Severny Island 30 km to the northwest as far as the frontal part of the Serp-i-Molot outlet glacier (Fig. 1a). The width of the bay here is 3–3.5 km, with the depth of 60–70 m in the center of the front. The terminal moraine, which extends across the bay from southwest to northeast is 0.5–0.8 km from the front of the glacier at depths from 8–10 to 20 m. The depths of the bay increase to 150 m or deeper to the southeast from the front of the glacier. The next rise in the bottom relief, at a depth of about 80 m is located ~4 km from the front of the glacier. A bit farther are Gorbaty and Bezymyanny islands, after which the depth increases again to 140 m. Another rise, determined by Kurgan, Tsivolky, and Krugly islands, is located at the outlet from the bay.

Sedov Bay cuts into the coast of Severny Island for about 20 km and has the configuration of a funnel with a somewhat curved lower part (Fig. 1b). The width and depth at the inlet to the bay are about 10 km and 145 m, respectively. In the central part of the bay, the width decreases to 1.5 km with depths shallower than 100 m. The remaining part of the bay stretches 9 km as a narrow fjord 0.6–1 km wide and 50–60 m deep.

MATERIALS AND METHODS

Samples were collected during cruises of R/V *Professor Shtokman* in 2014 and *Akademik Mstislav Keldysh* in 2015 and 2016 over the Kara Sea. Tsivolky Bay water was collected on all the three cruises; samples in Sedov Bay, on the latter two expeditions. In addition to bay water, that of local streams were sampled, along with water from the Serp-i-Molot glacier in Tsivolky Bay. Water from the St. Anna and Voronin troughs were sampled on the 2015 expedition. All samples except those from the streams and glacier were collected with bottles of an SBE 32 set during hydrophysical probing. The vertical profiles of the temperature and salinity distribution, along with the δD and $\delta^{18}O$ values, were examined for each station.

Oxygen isotope analysis was carried out with a DELTA V+ set manufactured by

Thermo Co. (Germany) using the Gas Bench II option under a constant helium flow. The isotope composition of hydrogen was analyzed based on the decomposition on metallic chromium (H/Device option) and measured within dual inlet system by DELTA plus mass spectrometer (Thermo Co., Germany). All δD and $\delta^{18}O$ values were calibrated on a V-SMOW–V-SLAP scale and determined with accuracies of ±0.05 and ±0.3‰, respectively.

RESULTS

Table 1 summarizes the isotope characteristics of all potential fresh water sources for Novaya Zemlya bays. The samples of local streams were collected both in the coastal zones of the bays and on the water surface. The

Table 1. Systematics of isotope parameters of potential sources of water freshening in bays of southeastern coasts of Novaya Zemlya Archipelago

Fresh water types	$\delta^{18}O$, ‰	δD, ‰	*d*
Snow at high latitudes [21]	–24...–25	~–200	
Atmospheric precipitation in region [17, 2]	–23.0	–173.0	11.0
Ob estuarine water [2, present study]	–15.5	–115.8	8.3
Yenisei estuarine water [2]	–19.3	–145.3	9.2
Streams in Tsivolky Bay [present study]	–15.6	–111.5	13.3
	–16.5	–118.2	13.8
Waterflows in Sedov Bay [present study]	–15.4	–112.8	10.4
	–12.7	–97.1	4.6
	–16.1	–116.3	12.5
	–16.0	–114.6	13.7
	–15.6	–112.2	13.0
	–14.6	–105.2	11.6
Serp-i-Molot glacier [present study]	from –17.6 to –15.7	from –125.5 to –113.4	from 10.8 to 18.2

isotope parameters of local water (δD and $\delta^{18}O$) were slightly variable, about –110 and –15‰, respectively. The same parameters for ice from the Serp-i-Molot glacier showed wider variability: from –113.4 to –125.5 and from –15.7 to –17.7 ‰, respectively, for 22 samples. These ranges were similar to earlier published data (from –113 to –129.5 and from –15.5 to –17.8 ‰, respectively [5]).

The averaged δD and $\delta^{18}O$ values of Ob (–15.5 and –115.8‰) and Yenisei (–19.3 and –145.3‰) river runoff, as well as for the regional atmospheric component (–23 and –173‰), were taken from [1, 17]. These data were supplemented by the authors' results, for example, for the hydrogen isotope composition of Ob estuarine water.

The data in Table 1 for freshwater flows sampled in both bays were close to the composition of Serp-i-Molot glacier ice. The tabulated data show that Ob estuarine water was indistinguishable in isotope characteristics from water supplied from the Novaya Zemlya Archipelago. Conversely, Yenisei estuarine water and atmospheric precipitation in the region were characterized by a considerably lighter hydrogen and oxygen isotope composition (Table 1), which makes it possible one identify these waters against other freshwater components.

Water of the bays. The waters of all the processed stations were characterized by a similar dynamics of the δD distribution, increasing with depth (Fig. 2). The behavior of $\delta^{18}O$ and salinity values was similar. However, variations in these parameters were recorded exclusively above the halocline; no interannual variations of isotope parameters were noted in deeper water. Figure 2 shows that the lightest hydrogen isotope composition was characteristic of surface water of the bays in 2015, when the salinity decreased to 24. The points from waters from both bays in the δD–$\delta^{18}O$ diagram deviate from the ideal two-component mixing line and show scattering within the ranges of both minimum and maximum desalination (domains I and II in Fig. 3). The isotope composition–salinity diagrams (Figs. 4, 5) also showed no pronounced linear correlation for the bay waters, which indicate a complex freshening mechanism.

DISCUSSION

Freshening processes are commonly considered within isotope composition–salinity coordinates, and the $\delta^{18}O$ value is usually taken as the isotope parameter [11, 23]. The present study considers the correlation of the isotope composition in S–δD coordinates (Figs. 4, 5) completely analogous to S–$\delta^{18}O$ coordinates. To consider the isotope characteristics of freshened water with several types of freshwater components, the authors propose an approach that compares the observed compositions to reference lines conforming to the two-component mixing of all potential fresh water sources and a single "marine" component. The S–δD diagrams in Figs. 4 and 5 plot the lines corresponding to mixing of Atlantic water prevalent in the Kara Sea and the freshwater components systematized in Table 1. The data obtained for the bay waters are considered with respect to these reference lines of two-component mixing.

The isotope parameter of potential desalination sources for the Novaya Zemlya bays vary widely (Table 1), yielding an obvious discrepancy between the measured characteristics and the two-component mixing lines. Water modification under ice formation

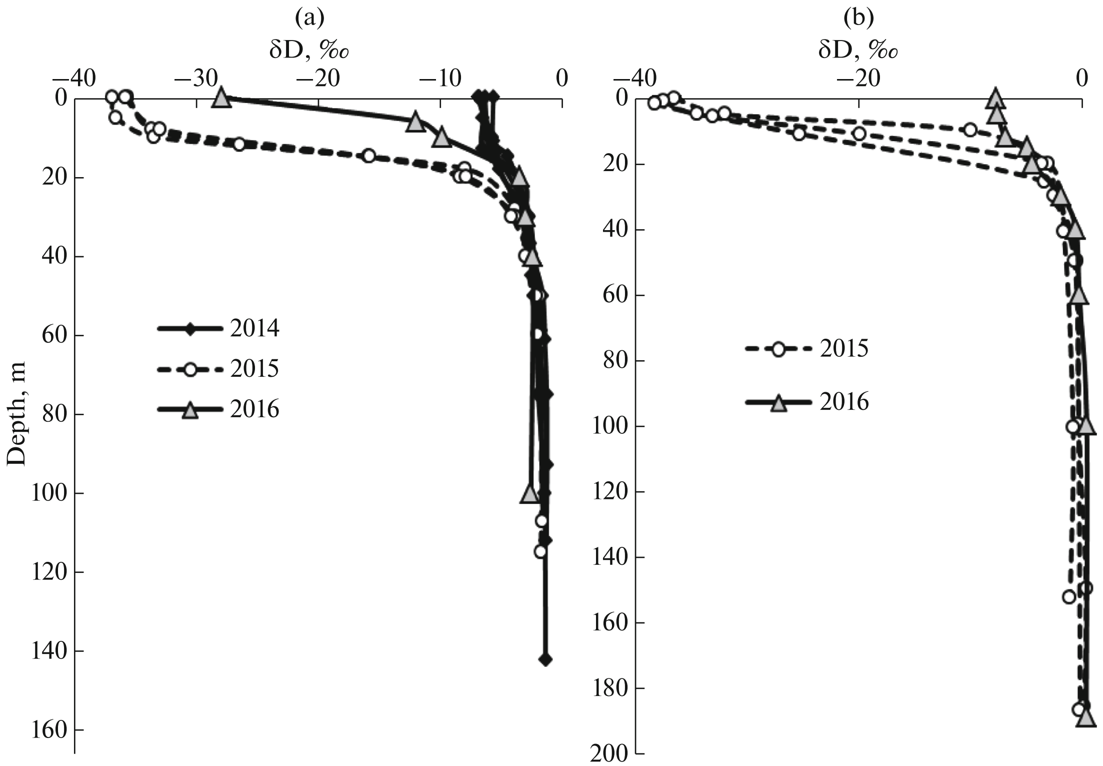

Fig. 2. Vertical distribution of hydrogen isotope composition in water of Tsivolky (a) and Sedov (b) bays in different years.

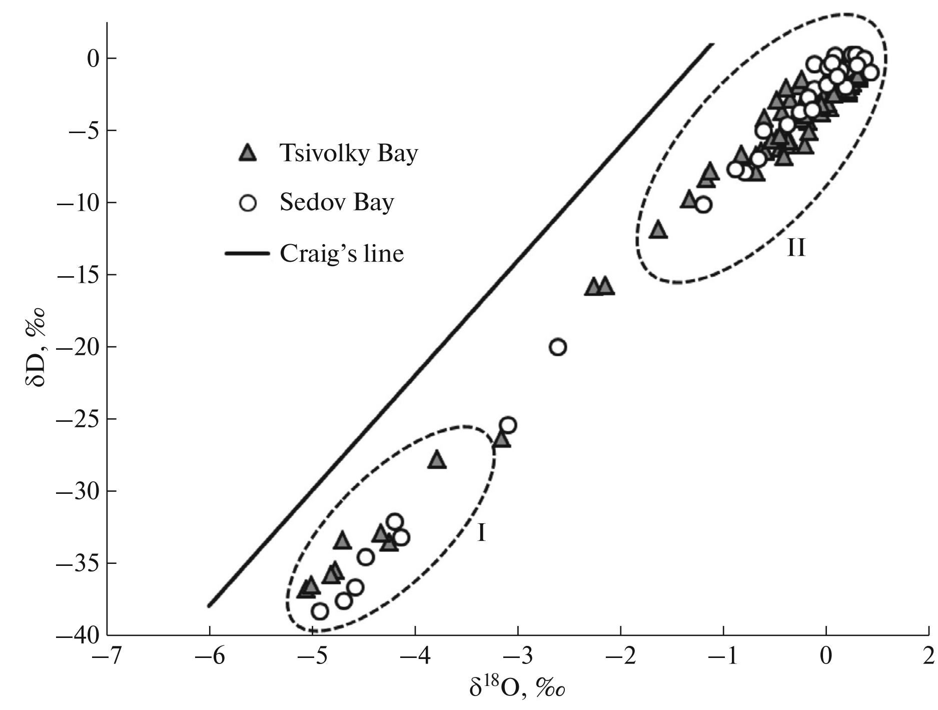

Fig. 3. Isotope composition of oxygen and hydrogen in water of Novaya Zemlya bays: I, water of halocline; II, water below halocline.

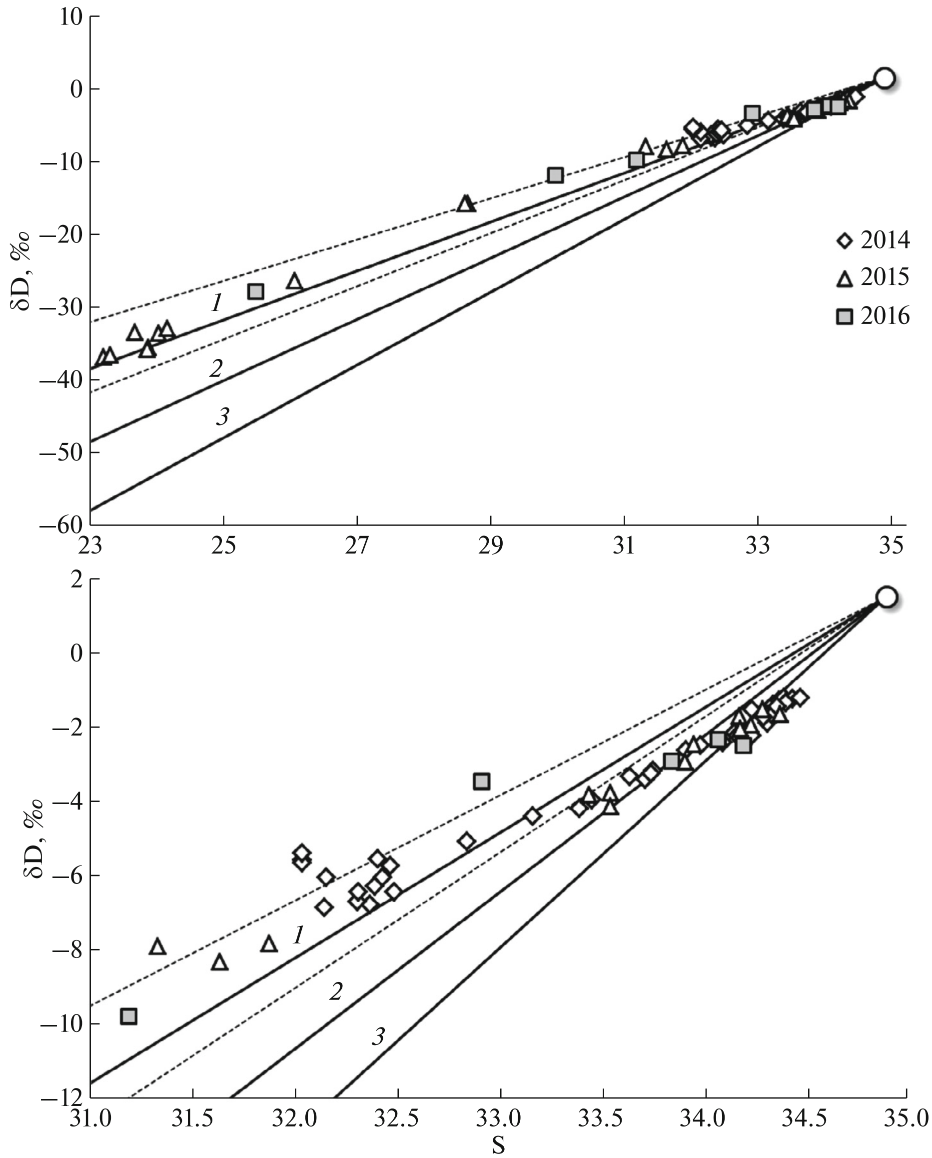

Fig. 4. Hydrogen isotope composition and water salinity in Tsivolky Bay: (a) all water sampled in 2014–2016, (b), weakly freshened water ($S > 31$). Lines *1*, *2*, and *3*, mixing of marine component of Atlantic origin with water of Ob and Yenisei rivers along with regional atmospheric precipitation, respectively. Dotted line denotes area of compositions characteristic of two-component mixing with water supplied from Novaya Zemlya Archipelago.

is usually treated as the reason for data scattering in S–δD coordinates. Despite the fact that ice formation is characteristic of the bays of the Novaya Zemlya Archipelago, this process is probably subordinate for the water modification should cause the data scattering at high salinities. On the contrary, the data scattering for Sedov and Tsivolky bays increases at low salinities. Moreover, the water located under the halocline in the two bays of different openness degrees, depths, and bottom relief, are identical in salinity (Fig. 6) which testifies against their modification expressed as a rule locally. The occasional points above all the lines of two-component mixing in the diagrams of Figs. 4 and 5 may be considered as a result of the occurrence of melted marine ice in the samples.

Water desalination in Tsivolky Bay. All the survey data in S–δD diagram lie within a unified sequence (Fig. 4a), which points to temporal constancy of the isotope parameters in the main fresh water sources of the bay. The most freshened water from Tsivolky Bay ($S \approx 24$–30) sampled in 2015–2016 occurred within the upper layers (0–6 m at station 5386 and 0–15 m at stations 5251, 5252, and 5253). This water was characterized by low δD and $\delta^{18}O$ values (from −9 to −37‰ and from −1.6 to −5.1 ‰, respectively) and plotted in the field of freshening by meltwater from the Serp-i-Molot glacier (bounded by dotted lines in Fig. 4a), as well as to the line of mixing with Ob River water within the same area. Water with a salinity below 25 plotted immediately near the line of mixing with Ob River

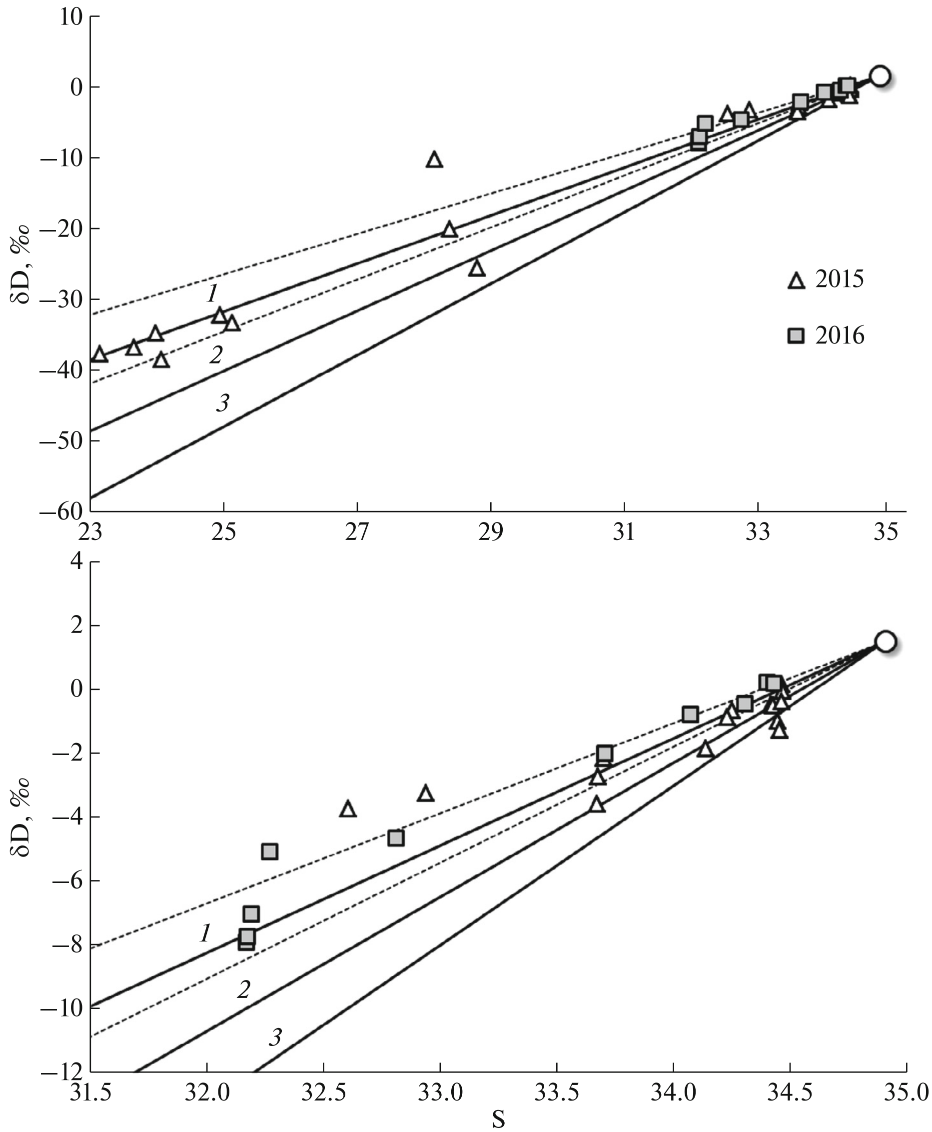

Fig. 5. Hydrogen isotope composition and water salinity in Sedov Bay: (a), all water sampled in 2015–2016 and (b) weakly freshened water ($S > 31$). See Fig. 4 for notation.

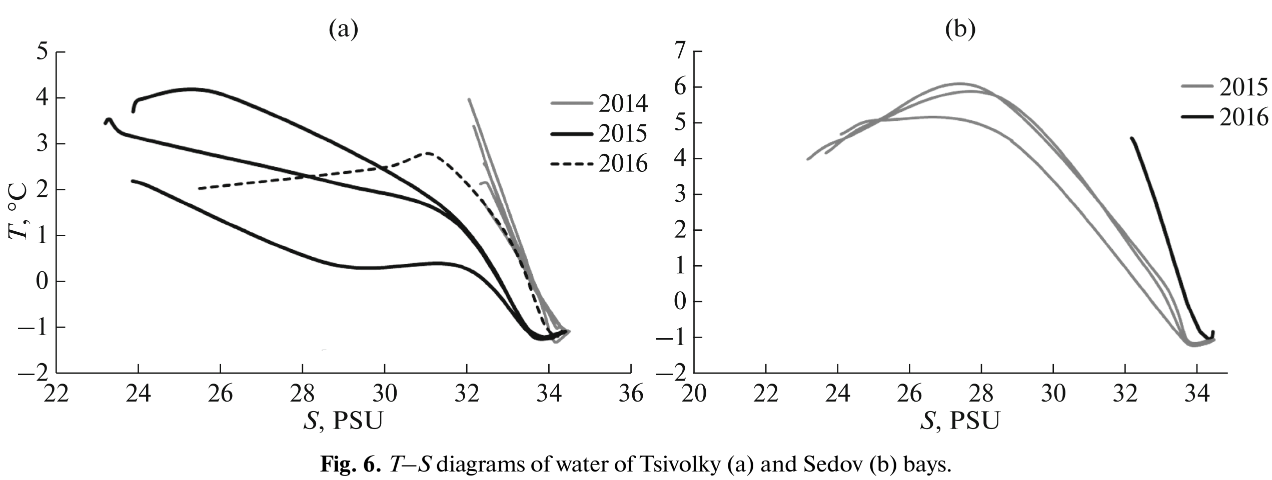

Fig. 6. *T*–*S* diagrams of water of Tsivolky (a) and Sedov (b) bays.

Table 2. Parameters of least freshened water in bays of Novaya Zemlya Archipelago

	Depths	$\delta^{18}O$, ‰	δD, ‰	S	T, °C
Tsivolky Bay, $n = 9$	60–142	0.25 ± 0.2	–1.3 ± 0.2	34.39 ± 0.04	–1.07 ± 0.04
Sedov Bay, $n = 14$	40–189	0.15 ± 0.2	From –1.8 to 0.3	34.35 ± 0.13	–1.03 ± 0.1
Atlantic water		0.26 ± 0.1	+1.55 ± 0.4	34.95 ± 0.05	
St. Anna Trough	10–90	–0.1 ± 0.1	From –2.8 to –0.3	34.35 ± 0.13	From –0.6 to 5
Voronin Trough	30–115	0.16 ± 0.2	From –1.8 to 0.8	34.24 ± 0.15	–1.02 ± 0.4

water or local runoff from the archipelago. A freshwater component could not be identified more precisely, because the considered freshwater isotope parameters were close to each other (Table 1).

The least freshened water in Tsivolky Bay ($S > 34$) occurred below the halocline at depths of 40–142 m. This water in the S–δD diagram (Fig. 4b) lies along the two-component mixing line with a regional atmospheric component, but without complete coincidence, and is characterized by stable salinity, temperature, and isotope composition parameters for three years (Table 2). Compared to Barents Sea water originating in the Atlantic (Table 2), the salinity of this water decreased to ≈34.5, which indicates presence of about 1.3–1.5% of freshwater component. According to the material balance, this component should be of less than –200‰ δD. A similar estimate of the $\delta^{18}O$ value for the same component is difficult to obtain because of the large error in the balance calculation for $\delta^{18}O$ values close to zero. Assuming that the freshwater component was atmospheric (i.e., from precipitation), its $\delta^{18}O$ value can be calculated from Craig's equation, rewritten as

$$\delta^{18}O = (\delta D - 10)/8.$$

Calculation by this equation for δD ~ –200‰ yields $\delta^{18}O$ ~ –24‰.

Tsivolky Bay water at medium depth (20–40 m) was characterized by intermediate salinity ($33 < S < 34$) and formed the trend (Fig. 4b) of a secant to all two-component mixing lines. The position of this trend showed that this depth range was characterized by mixing of very freshened surface water with the least freshened underlying water.

Water freshening in Sedov Bay. The data for Sedov Bay water in S–δD coordinates showed a behavior different from those for Tsivolky Bay (Fig. 5a). Water with minimum freshening degree ($S > 34$) at depths of 40–189 m was characterized by close temperatures and oxygen isotope compositions to the values for the least freshened water of Tsivolky Bay. However, this water showed pronounced variations in the hydrogen isotope composition, in contrast to Tsivolky Bay. Thus, in the S–δD diagram (Fig. 5b), the most saline water with S ~ 34.5 formed a vertical dispersion of δD values from –1.8 to 0.3‰, exceeding the analytical error by severalfold (±0.3‰). The constant hydrophysical characteristics—temperature and salinity—pointed to a single water mass located at depths below 40 m in both bays. However, pronounced variations in the hydrogen isotope composition indicated the participation of at least two different components in forming the minimally freshened water of Sedov Bay. According to the balance calculation, these components should be freshened by two types of water showing δD values below –200 and about –100‰ in order to form the observed vertical dispersion in the area of S ~ 34.5. One of these components was similar to the deep-water freswater component in Tsivolky Bay; the other showed a hydrogen isotope composition similar to that of local fresh water sources and Ob estuarine water.

The area of medium and low salinity in Sedov Bay were characterized by the same regularities as those in the least freshened water, i.e., isopycnic mixing of two water masses freshened by components with contrast isotope parameters. Mixing proceeded in areas of differing salinity, which resulted in vertical dispersion of points in the S–δD diagram. The last pronounced mixing event was seen in the area of $S \approx 28$, where the mixing waters had the most different isotope parameters (Fig. 5a). These water were collected at depths of 10–11 m at three different stations (nos. 5242–5244). In addition to close salinities, these waters had close temperatures (≈5°C), i.e., uniform in density, which probably caused the isopycnic mixing. The distribution of the isotope parameters for Sedov Bay in 2015 suggested not only high reshening degree, but also great variations in the isotope composition of freshwater components. The most freshened water collected at shallow depths (0–6 m) showed a decrease in salinity to 24, which conformed to the 28–33% contribution of the freshwater component. The points conforming to the most freshened water of the surface layer in the S–δD diagram were on the line of two-component mixing with either Ob River water or a local component.

Freshwatersources and mechanisms in Tsivolky and Sedov bays. The data showed that water of both bays at all depths during all years of observation was freshened against Barents Sea water of Atlantic origin prevalent in the Kara Sea. However, the freshening degrees and sources of freshwater components were different for water at different depths. Table 3 summarizes the esti-

Table 3. Evaluation of contribution of freshening water (%) in Sedov and Tsivolky bays

Years of sampling	Surface water, 0–15 m	Water of intermediate zone, 15–40 m	Water below halocline, 40 m–bottom
		Tsivolko Bay	
2014	3.8–7.1	1.4–4.7	1.2–2.3
2015	16.9–32.7	2.7–9.1	1.5–2.1
2016	9.5–26.1	1.8–4.5	2.0–2.4
		Sedov Bay	
2015	16.3–32.8	2.2–5.4	1.3–2.2
2016	6.3–6.6	4.8–6.3	1.4–2.4

mates of the overall freshwater contribution at various depths during different years of observation. The freshwater contributions were calculated based on the mechanism of mixing of surface-layer water with water below the halocline. In other words, the parameters of water below the halocline in a given bay were applied as the "marine" component for these deep waters.

The least freshened deep water in both bays was similar not only in physical (salinity and temperature) but also in isotope parameters (Table 2). These water contained about 1–2% of freshwater component with δD and $\delta^{18}O$ values lower than the averaged values of the regional atmospheric component (–173 and –23‰, respectively) for 76°–78° N [17, 2]. Snow with δD and $\delta^{18}O$ values of about –200 and –25‰ or less, respectively, was occasionally found in the region of Svalbard and Franz Josef Land [21]. Atmospheric precipitation with isotope characteristics as such was more persistent in the North Pole region: snow with δD < –200‰ was collected by the *Barneo 2013* and *Barneo 2014* expeditions [6]. For the most part, based on the data of IAEA stations [21], atmospheric precipitation with low δD and $\delta^{18}O$ values in the Arctic were characteristic of northwestern Canada and Greenland rather than of the Novaya Zemlya Archipelago and the Kara Sea. This was also confirmed by the isotope parameters of the Serp-i-Molot glacier, consisting of the accumulated long-term atmospheric precipitation (present study and [5]). Hence, the isotopically light component of atmospheric precipitation at higher latitudes should be transported to the bays of the Novaya Zemlya Archipelago with water supplied from the Arctic Ocean. The most probable route for this passes through the northeastern Kara Sea, where the St. Anna and Voronin troughs are situated [16]. Figure 7 compares the least freshened water of the considered bays to water sampled in the area of the St. Anna and Voronin troughs and characterized by the same salinity range (34.5 > *S* > 34). Water with such salinity values is located at depths of 10–90 and 30–115 m near the St. Anna and Voronin troughs, respectively. The closeness of the isotope parameters for the least freshened water in the bays and analogous water parameters at medium depths near the St. Anna and Voronin troughs agrees with the description of hydrological regime in the Kara Sea, indicated that Arctic Ocean water could be supplied to the Kara Sea via these troughs [7].

The vertical distribution of the freshening component represented by polar atmospheric precipitation was different in the two bays (Fig. 8). The occurrence of this component was very pronounced for Tsivolky Bay: beginning at a depth of 50 m, the calculated δD values fell stably outside the ranges determined for regional atmospheric precipitation at 76–78° N. At depths from 50 m to the bottom (about 150 m), the calculated δD values of the freshening component were within the range from about –190 to –200‰.

The occurrence of an isotopically light freshening component in Sedov Bay was recorded in two samples from depths of 100–150 m. The other calculated compositions indicated entrainment of fresh water with isotope parameters characteristic of river continental runoff and local runoff from the Novaya Zemlya Archipelago. Thus, Sedov Bay was characterized by intense mixing of water supplied via the St. Anna and Voronin troughs with water freshened either within the bounds of the Kara Sea or immediately at the coasts of the archipelago. No mixing as such was observed in Tsivolky Bay, where water located below the halocline showed no indications of mixing with in situ freshened near-bottom Kara Sea water. This conclusion agrees with different bottom surface morphologies in the bays. Whereas Tsivolky Bay was characterized by several bottom elevations along with island chains preventing free water exchange with the Kara Sea, there were no such barriers in Sedov Bay except for a slightly expressed saddle in the central part, with depths of about 25 m.

Potential fresh water sources for the haloclines of the both bays may consist of both local runoff from the Novaya Zemlya Archipelago and estuarine water of the Ob and Yenisei rivers. As noted above, the maximum fresh water content may be over 30% in the surface water of bays, which should be close to the estimates of river water content in the freshened surface layer occurring in the center of the Kara Sea (up to 40%, [1]). The probable propagation of river runoff to the coasts of the Novaya Zemlya Archipelago should be different for Ob and Yenisei estuarine water, since

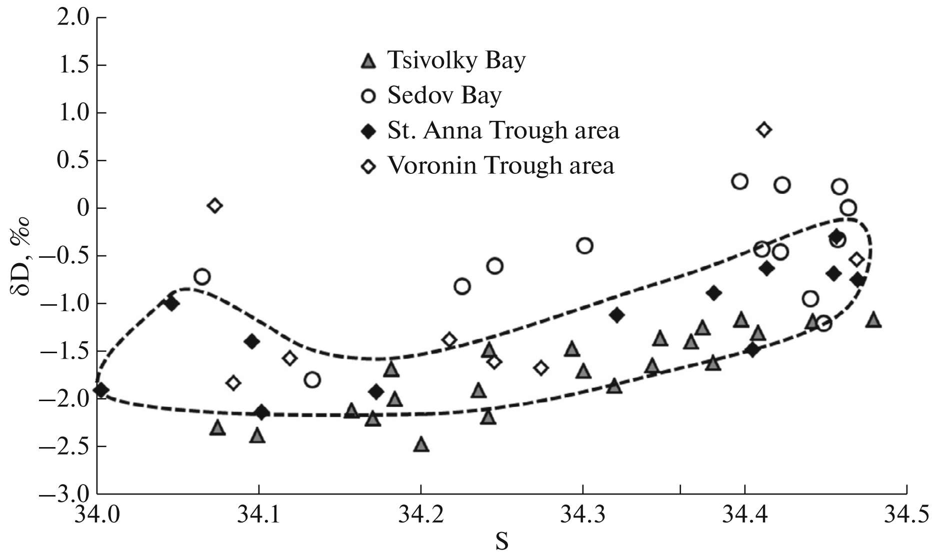

Fig. 7. Least freshened water of Novaya Zemlya bays and water collected in region of St. Anna and Voronin troughs. Principal part of water is marked with dotted line.

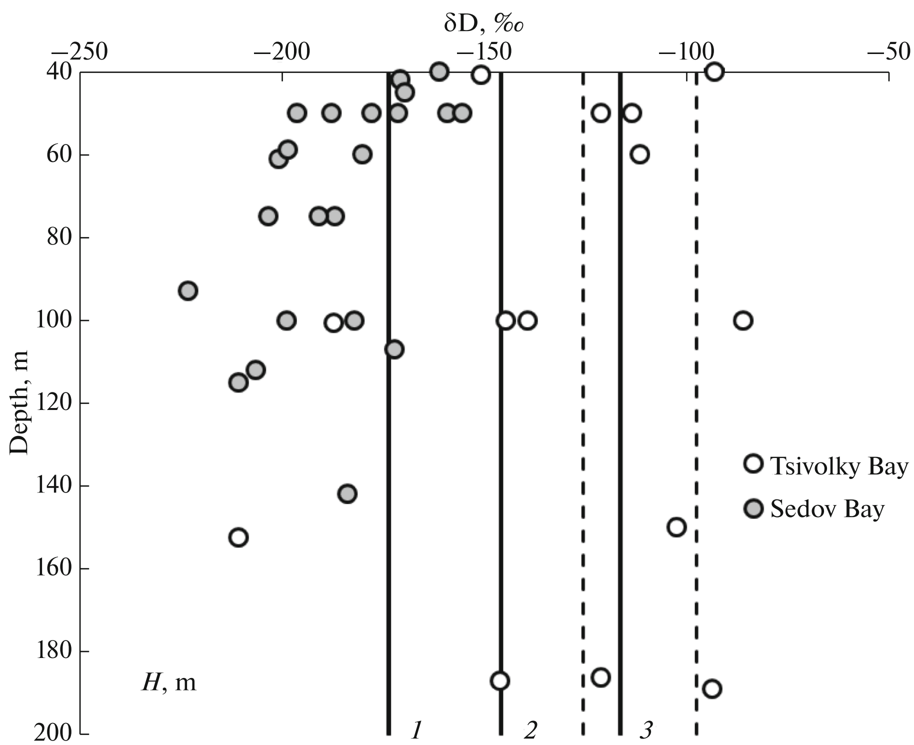

Fig. 8. Hydrogen isotope composition of freshening component of Tsivolky and Sedov bay waters below halocline. Vertical lines show compositions of averaged runoff of atmospheric precipitation (*1*) and Yenisei (*2*) and Ob (*3*) rivers. Dotted lines mark field of composition of fresh water supplied from Novaya Zemlya Archipelago.

each of the rivers was characterized by specific seasonal discharge dynamics [19]. Based on Russian hydrometeorological service data [26], total Yenisei runoff in 2015 was close to that of the Ob, exceeding the latter only by 15%. However, about 50% of Yenisei runoff fell within May–June, whereas the summer runoff of the Ob was steady during the entire warm season (Fig. 9). Hence, the plumes of Ob River water in 2015 might have propagated over the Kara Sea surface for a longer time, increasing the probability of

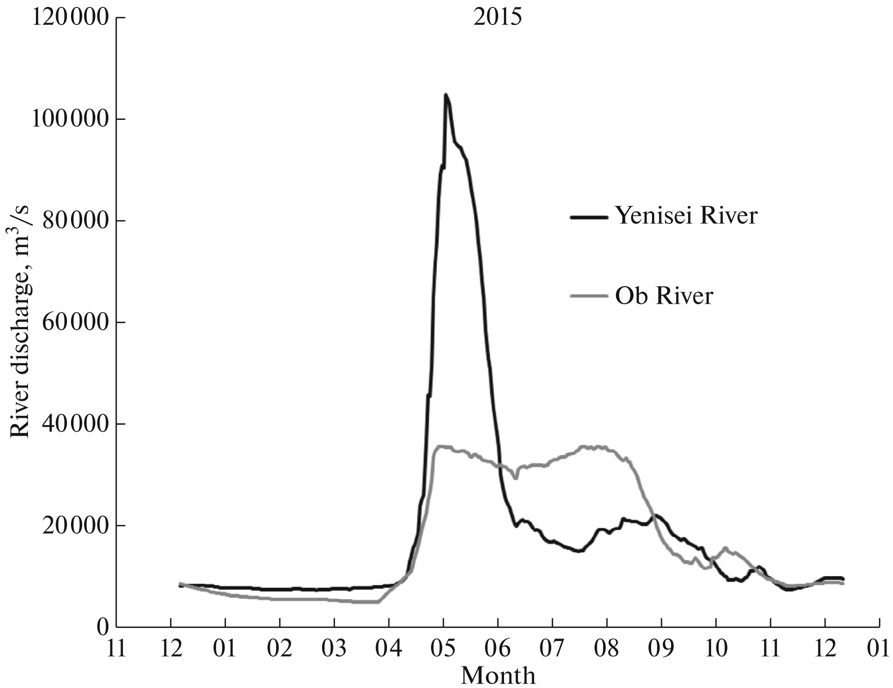

Fig. 9. Dynamics of Yenisei and Ob river runoff based on Russian hydrometeorological service data for 2015 [26].

their occurrence in Sedov Bay during August–September when the samples were collected. Nevertheless, the closeness of the isotope parameters of Ob estuarine water and streams from the coasts of the Novaya Zemlya Archipelago hindered characterization of river water's contribution to surface water in the bays.

Table 4. Seasonal variations of isotope parameters of surface and underice water of Yenisei and Ob rivers based on ArcticGRO Project data [20]

	δD	δ^{18}O	*d*
		Ob River	
January	–113	–14.9	6.4
March	–144	–19.3	10.1
May	–149	–20.1	11.5
July	–111	–14.7	6.8
September	–110	–13.8	0.7
November	–108	–15.0	11.2
		Yenisei River	
January	–135	–18.7	14.2
March	–135	–18.5	12.8
May	–135	–18.2	10.5
July	–137	–18.2	7.9
September	–128	–17.6	12.4
November	–132	–18.4	14.6

Our analysis for the two isotope system of water molecule (δ^{18}O and δD values) make it possible to use the additional parameter of deuterium excess *d*, calculated by the equation [15]

$$d = \delta D - 8\delta^{18}O.$$

The *d*-excess characterizes the formation conditions of atmospheric moisture as the source of all freshening components [22, 10]. A unique feature of atmospheric precipitation in the region of the Kara Sea and Novaya Zemlya Archipelago is a stably high *d* values of about 13–14, on average, occasionally up to 20‰ or more. This parameter varies seasonally for the Ob and Yenisei rivers; nevertheless, it is considerably lower than that for atmospheric precipitation falling in the area of the Novaya Zemlya Archipelago. Thus, according to the database of the ArcticGRO project [20], from late July to late September 2015, the *d* values were 0.7–6.8 and 7.9–12.4‰ in Ob and Yenisei waters, respectively (Table 4). The considerable difference in these values allows to apply *d*-excess for more detailed identification of water freshening sources in the bays of the Novaya Zemlya Archipelago.

We should mention that calculation of *d*-excess in a freshening component would be meaningful exclusively for water with high degrees of freshening; otherwise, the calculation might yield improbable or erroneous estimates for *d*. That was why the calculations exclusively concerned surface water of the bays based on the example of 2015, when water freshening was maximum. Figure 10 shows the calculated *d* values and

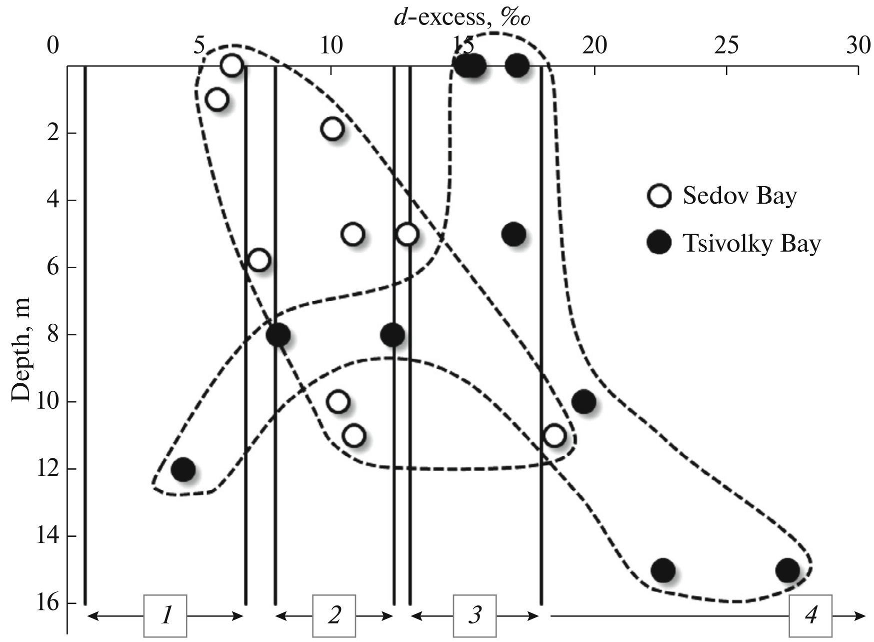

Fig. 10. Calculated *d*-excess in freshening component of surface water of Tsivolky and Sedov bays in 2015. Ranges characteristic of potential sources of freshening: (*1*) Ob River water during July–September 2015; (*2*) Yenisei River water during same time; (*3*) local runoff from Novaya Zemlya Archipelago and local atmospheric precipitation; (*4*) mainly meltwater from glacier.

ranges of *d*-excess conforming to the main potential sources of water freshening in the Novaya Zemlya bays. Comparison of the *d* values calculated for the freshening component of surface water in Sedov Bay to these ranges showed that this component consisted of Ob River estuarine water. The river component was gradually substituted with depth by local runoff from the archipelago, distinctly identified even at depths of 10–12 m.

The surface layer of Tsivolky Bay was characterized by the prevalence of water of local freshening sources. The occurrence of Ob River water was revealed only in three samples collected from depths of 8–12 m. At depths of 10–15 m, the glacier component began to predominate among the local freshened water, which was characterized by abnormally high *d*-excess values similar to the *d* values in some samples from the Serp-i-Molot glacier.

Analysis of the diagram in Fig. 10 makes it possible to suggest different mechanisms for the freshening of bay water that occurred in 2015. Ob estuarine water was probably supplied to Sedov Bay as a plume transported over the sea surface; the water freshened by local runoff from the Novaya Zemlya Archipelago occupied an underlying position. Despite the similar degree of freshening in Tsivolky Bay, no plumes of Ob or Yenisei water were seen on the surface. The occasional appearance of water freshened by continental runoff at intermediate depths may have resulted from intrusions of Kara Sea water into the bay. Evidently, the difference in surface water freshening mechanisms in the two bays was determined by the degrees of their isolation, i.e., by the presence of natural barriers to exchange of surface water with the Kara Sea in Tsivolky Bay and the absence of such barriers in Sedov Bay. Direct outflow from the Serp-i-Molot glacier into Tsivolky Bay, along with the absence of glacier outflows in Sedov Bay, can be considered as significant factors.

CONCLUSIONS

The proportions of local and global d freshening sources in the bays of the Novaya Zemlya Archipelago are nonuniform in depth. Water from continental runoff occurs mainly within the surface layer. The freshwater component consisting of high-latitude atmospheric precipitation is found exclusively in water below the halocline. The local freshening component of runoff from the Novaya Zemlya Archipelago is found both in surface water (Tsivolky Bay) and below the halocline (Sedov Bay). Evidently, the distribution of the freshening component is specific to each of the bays and determined by geographic and morphological features, bottom relief, and openness of the water areas.

The study proposes new approaches making it possible to estimate the proportions of different fresh water sources during multicomponent mixing. In isotope composition–salinity coordinates, the technique of a set of reference lines of two-component mixing can be applied, with respect to which it is possible to trace variations in the ratios of the freshening components with decreasing salinity. Calculation of *d*-excess can be used for water with close isotope characteristics. These approaches are applicable to study other regions of the World Ocean.

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