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GEOGRAPHY

Oxygen Isotope Composition of Water and Snow–Ice Cover of Isolated Lakes at Various Stages of Separation from the White Sea

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Abstract—This study aimed to analyze the oxygen isotope composition of water, ice, and snow in water bodies isolated from the White Sea and to identify the structural peculiarities of these pools during the winter period. The studies were performed during early spring in Kandalaksha Bay of the White Sea, in Velikaya Salma Strait and in Rugoserskaya Inlet. The studied water bodies differ in their degree of isolation from the sea. In particular, Ermolinskaya Inlet has normal water exchange with the sea; the Lake on Zelenyi Cape represents the first stage of isolation; i. e., it has permanent water exchange with the sea by the tide. Kislo-Sladkoe Lake receives sea water from time to time. Trekhtsvetnoe Lake is totally isolated from the sea and is a typical meromictic lake. Finally, Nizhnee Ershovskoe Lake exhibits some features of a saline water body. The oxygen isotope profile of the water column in Trekhtsvetnoe Lake allows defining three layers; this lake may be called typically meromictic. The oxygen isotope profile of the water column in Kislo-Sladkoe Lake is even from the surface to the bottom. The variability of $\delta^{18}O$ is minor in Lake on Zelenyi Cape. A surface layer (0–1 m) exists in Nizhnee Ershovskoe Lake, and the oxygen isotope variability is well pronounced. Deeper, where the freshwater dominates, the values of ?18Îvary insignificantly disregarding the water depth and temperature. This fresh water lake is not affected by the seawater and is not stratified according to the isotope profile. It is found that applying the values of ?18Î and profiles of temperature and salinity may appear as an effective method in defining the water sources feeding the water bodies isolated from the sea environment.

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The functioning of the White Sea ecosystem is affected by the hydrogeochemical processes taking part in its watershed area [1]. However, the process of the isolation of the water bodies on the shoreline of the White Sea due to eustatic uplift has not been studied well [2–4].

The evolution of such water bodies includes several stages [5]. The first stage is characterized by ongoing water exchange at high tide despite the riffle; however, the water of the main hollow starts to separate structurally. When the riffle becomes too high to be overcome by high tide, but does not block the discharge of the surface waters to the sea, the second stage occurs. This is the stage of the isolated water body, which has no exchange with the sea, but cannot be described as belonging to the terrestrial ecosystem [6]. Further uplift of the riffle leads to the third stage. The surface water layer is presented by fresh water, but the hollow keeps a salty environment. This is the stage of a meromictic waterbody. Such pools are found in Russia quite rarely [7–10], and their total number barely exceeds two hundred [11, 12].

Studies of isolated water bodies are important for finding the relative fluctuations of the sea level in the Holocene with regard to climatic changes. The bottom sediments of both the sea and the isolated water bodies are usually analyzed for assessing the long-term changes during last 10 000 years [2–5]. For studying the short-term events that took place in recent years or even months, measurements of the hydrophysical properties and oxygen isotope composition are necessary. The concentration of the stable isotopes of oxygen in the water, ice, and snow is an important indicator of the ice regime and water stratification [13, 14].

In the White Sea, due to the peculiarities of its morphology, the isolating waterbodies are quite variable. Comparative studies of the water bodies at different stages of isolation were previously performed only the summer period [6, 15], and winter-related data are totally absent.

This study aims to investigate the oxygen isotope composition of water, ice, and snow in the water bodies isolated from the White Sea and to identify the structural peculiarities of these water bodies in the winter period.

The studies were performed during a complex expedition in Kandalaksha Bay of the White Sea, in the vicinity of the White Sea Biological Station of Moscow State University from March 20 to April 2, 2012. Field sampling was performed in the water bod-

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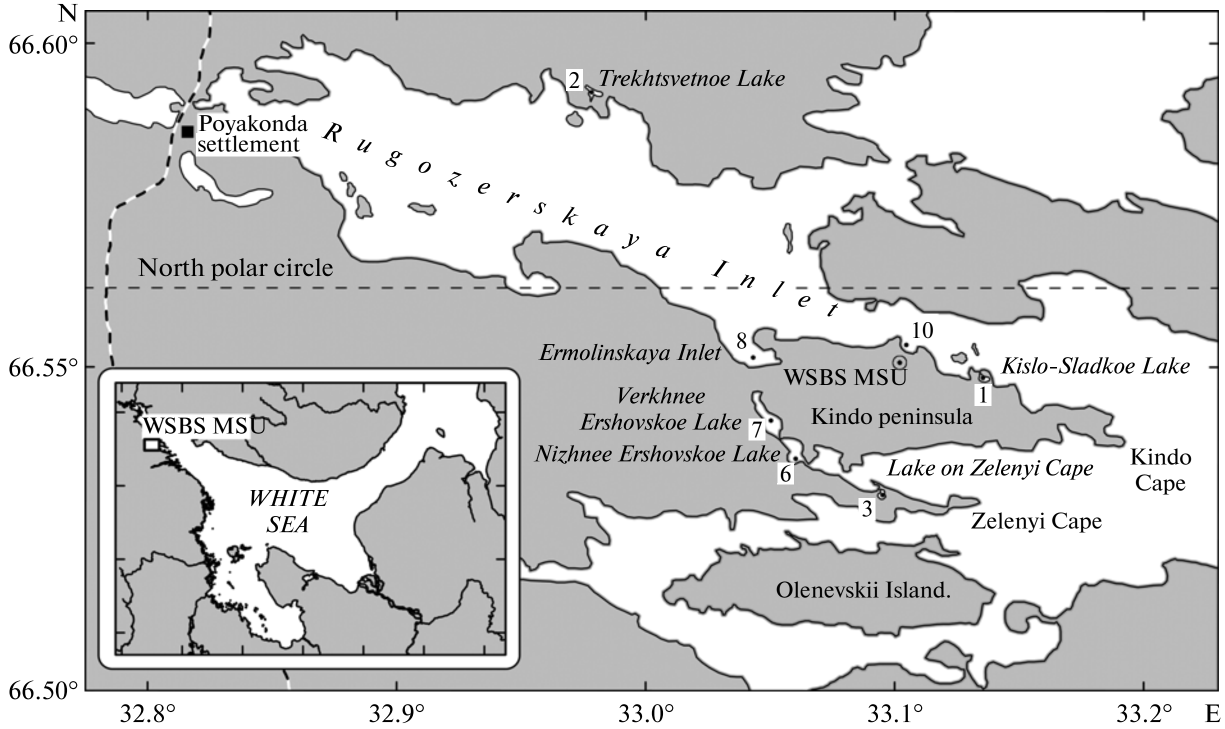

Fig. 1. Sampling site map on Kindo Peninsula (Kandalaksha Bay, the White Sea). The NE location of sampling sites and sampling depths are presented in Tables 1 and 2.

ies of different stages of isolation from the sea, in Velikaya Salma Strait and in Rugoserskaya Inlet in early spring. The hydrophysical and isotope properties of the lake water, ice, and snow were studied. Five lakes were studied (Kislo-Sladkoe, Trekhtsvetnoe, Verkhnee Ershovskoe, Nizhnee Ershovskoe, and Lake-on-Zelenyi-Cape), Ermolinskaya Inlet, as well as the snow in the vicinity of the WSBS MSU pier (Fig. 1; Table 1).

The water was sampled at different depths using a hosepipe and a sinking pump. The water temperature and salinity were measured with 0.5-m discontinuity by a PrifiLine Cond 197i conductometer. The snow was placed into sterile plastic bags. The ice cores were sampled with a titanium ring-type corer, divided by the layers that differed visually by the ice structure, and placed into sterile plastic bags. The snow and ice samples were melted gradually at 16–18°C.

The samples of water, ice, and snow were analyzed in the Stable Isotope Laboratory, Geographical Faculty, Moscow State University, using the Delta-V mass-spectrometer with a standard option of a gasbench according to standard methods. The accuracy of the measurement was ±0.04‰ with regard to $\delta^{18}O$. In analyzing the $\delta^{18}O$ concentration, the samples were equilibrated with CO_2 for 24 hours. The international standard of the oceanic water SMOW-V and laboratory standards of IAEA and Austrian Technical University were used as the reference concentrations.

The studied water bodies differed in their degree of isolation from the sea. In particular, Ermolinskaya Inlet has normal water exchange with the sea. Lake-on-Zelenyi-Cape represents the first stage of isolation; i.e., it has continuous water exchange with the sea by the tide. Kislo-Sladkoe Lake receives seawater from time to time, but the discharge of the surface waters to the sea is not blocked. Trekhtsvetnoe Lake is isolated from the sea totally, which is proved by the fresh surface layer of 0–2 m and the bottom salty layer; these characteristics have remained stable for the last four years of observations (a typical feature of meromictic lakes). Upper Ershovskoe Lake is totally fresh. Nizhnee Ershovskoe Lake was previously defined as a fresh lake, since the last features of salinization were observed here 15 years ago. However, during the summer of 2011, some features of a saline water body were found again, when the salinity of the bottom water layer in the hollows reached 9 psu. Three types of dynamics were found in the studied lakes, seasonal, interannual, and catastrophic. The last occurs when high tides coincide occasionally with a wind-induced surge, and this causes penetration of the seawater into the isolated water body.

All the salty lakes studied were highly stratified both by temperature and by salinity, which was quite unusual for such shallow water bodies at the end of the winter season.

The upper 0.5-m water layer in Kislo-Sladkoe Lake was surprisingly salty (26.2 psu) in March 2012; usu-

Table 1. Sampling dates, sites, and activities performed in the vicinity of the White Sea Biological Station of Moscow State University (WSBS MSU), White Sea, March 26–30, 2012

Station	Station location	Date, dd.mm	N	E	Depth, m
3	Lake-on-Zelenyi-Cape	26.03	66°31.811′	33°05.702′	6
2	Trekhtsvetnoe Lake	27.03	66°35.548′	32°58.697′	6.5
8	Ermolinskaya Inlet	27.03 (snow) 29.03 (ice, water)	66°33.089′	33°02.589′	1.25
10	WSBS MSU pier	27.03	66°33.206′	33°06.279′	2
1	Kislo-Sladkoe Lake	28.03	66°32.900′	33°08.125′	4
7	Verkhnee Ershovskoe Lake	29.03	66°32.505′	33°03.018′	2.7
6	Nizhnee Ershovskoe Lake	30.03	66°32.151′	33°03.614′	1.6

ally, this layer stayed fresh (Fig. 2). The thermohaline water structure comprised two layers. The upper convective layer that promoted the ice formation and had low temperature of –1.4°C was surprisingly thin, about 0.5 m, while the ice thickness was also about 50 cm. Under the thermocline (2-m depth), there was a quasi-homogenous layer (–0.6°C; 27.6 psu). This layer was a consequence of seawater advection.

Trekhtsvetnoe Lake was characterized by a bilayer structure in the spring and summer period, according to the previous observations. There were an upper freshwater layer (about 2 m) and a lower salty layer enriched in hydrogen sulfide. The seasonal temperature fluctuations were observed for the layer of 0–5 m. In March 2012, the freshwater layer was absent; however, the bilayer structure remained. The surface layer (0–1 m) was presented by water of 5 psu and –0.3°C (Table 2, Fig. 2). Such salinization of the upper layer was possible if the seawater penetrated over the riffle. Below 1-m depth, the water temperature was above zero and even more than 4°C in the bottom water layer of 3.5–6.5 m. The salinity increased gradually from 17.3 up to 21.9 psu below 2-m depth. Salty water with a temperature above zero was registered for the first time for the depth of 1 m below the surface in the White Sea region.

Nizhnee Ershovskoe Lake was totally fresh during the previous summer, and some brackish water lenses (8.9 psu) were observed in the bottom hollows. However, in March 2012, even the surface water was of 1.1 psu, and below 1-m depth, the salinity was 16 psu. Alongside with that, the lower salty water layer was characterized by a temperature above zero; in one of the hollows located close to the sea it was 2.8°C, and in another hollow, located far from the sea, it was even more, 3.8°C. Therefore, we have observed twice the phenomenon of salty water with a temperature above zero registered at a depth of 1 m.

The smallest changes affected by the seawater advection were registered in the Lake-on-Zelenyi-Cape, where the thermohaline water structure also comprised two layers in March 2012. The upper homogenous water layer (0–4.5 m) was of 28.8 psu and –1.4°C, which referred to the freezing point within the measurement accuracy. Below 4.5-m depth, we registered an increase in both the salinity (29.3 psu) and temperature (0.2°C). Meanwhile, the salinity of the upper water layer that was exchanging the water with the lagoon through the riffle was significantly lower (25.9 psu). This means that such high water salinity is a result of water salinization in the lake hollows due to the formation of ice in the lake.

Verkhnee Ershovskoe Lake was totally fresh, as was also observed for the summer period. The ice structure and snow cover were studied for the isolated waterbodies. The ice cover thickness varied from 12 to 35 cm, and it was 9 cm on the ice of Ermolinskaya Inlet. The ice structure on the salty lakes had pronounced common features: the upper layer of 15–20 cm was presented by interlayers of opaque ice and liquid ice mass, the lower layer was characterized by a common structure of the sea ice (opaque layer, crystallized transparent layer, and the lowest one was porous). In Trekhtsvetnoe Lake, the lowest layer was presented by transparent fresh ice of 5-cm thickness.

The oxygen isotope vertical profile of the water column in Trekhtsvetnoe Lake was characterized by a high concentration of $\delta^{18}O$ in the bottom water layer (Fig. 2) and allowed defining three water layers in the water column: 0–2 m was the layer of mixolimnion, where the water changed from fresh to brackish, and $\delta^{18}O$ varied from –10.8 to –6.2‰; 2.0–3.8 m was a chemocline zone characterized by transitional features, the values of $\delta^{18}O$ varied from –5.9 up to –3.6‰; and 3.8–6.5 m was the zone of monimolimnion with extremely high salinity, which exceeded the values at the surface threefold, and with the highest values of $\delta^{18}O$, which varied from –3.6 up to +2.1‰; i.e., this lake might be called typically meromictic, like some other lakes [7–12].

The oxygen isotope profile of the water column in Kislo-Sladkoe Lake was even from the surface to the bottom (Table 2, Fig. 2a), the maximal variability of $\delta^{18}O$ was 1.2‰ and was registered in the transitional layer of 0.5–1.0 m, and the salinity also changed within this layer. The isotopic composition of the water

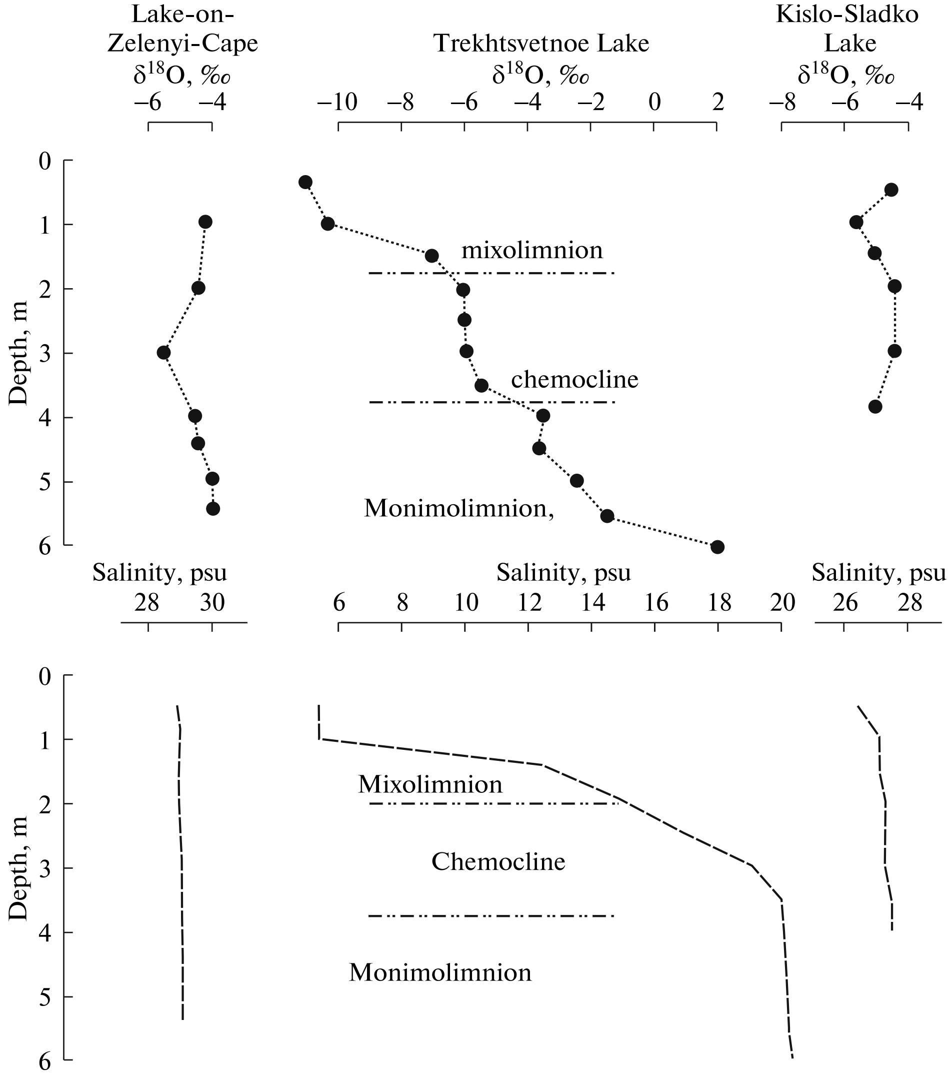

Fig. 2. Variability of $\delta^{18}O$ and salinity with regard to the water depth in the water bodies separated from the sea environment on Kindo Peninsula.

below 1-m depth is evidenced by a quasi-homogenous layer; these data fit well the hydrophysical profile. The advection of a huge volume of seawater during the winter period deteriorated the meromictic stratification of Kislo-Sladkoe Lake, unlike the isolated lakes located far from the shoreline [7–12]. The lake ice was characterized by a $\delta^{18}O$ range of –6.9 to –3.9‰. The formation of lake ice is most pronounced during the short period after the freezing begins, and this process takes place on both sides (upper and lower); therefore, we assume that the lower side of the ice was formed by salty water of the lake, and the upper side was mostly formed by snow.

The variability of $\delta^{18}O$ was minor in Lake-on-Zelenyi-Cape, from –4.01 up to –5.8‰ (Fig. 2), as was observed in Kislo-Sladkoe Lake. Meanwhile, the TS-profile was quite even (Table 2). This lake was characterized by an abnormally thin surface layer of 0.5 m; the water column structure was homogenous below (Fig. 2). The bottom water layer was not pronounced, which was probably linked with the active advection of the seawater.

The lake ice is characterized by an elevated concentration of heavy isotopes (–4.0 to –1.4‰), which occurs when the ice forms from the salty lake water without the participation of precipitation [14]. The variability of $\delta^{18}O$ in the ice is a result of isotope fractioning during ice formation.

The surface layer (0–1 m) exists in Nizhnee Ershovskoe Lake, and the oxygen isotope variability is well pronounced, from –11.7‰ at 0.5-m depth to –6.6‰ at 1.0-m depth. The water temperature and salinity also changed dramatically when the temperature increased from –0.4°C up to 2.4°C, and salinity changes from 1 to 16 psu. The ice of this lake is characterized by atmospheric isotope features, and both

Table 2. Temperature (T, °C), salinity (S, psu), and δ^{18}O (per mille) in the water and snow–ice cover of the studied water bodies located on Kindo Peninsula, Kandalaksha Bay, the White Sea

Station no. and location (as indicated in Fig. 1)	Sample	Sampling layer	T, °C	S, psu	δ^{18}O, ‰
1. Kislo-Sladkoe Lake	Fresh snow	0–2 cm	–	–	–14.47
	Total snow cover	0–15 cm	–	–	–8.19
	Ice	0–8 cm	–	–	–6.91
	″	8–15 cm	–	–	–4.83
	″	15–29 cm	–	–	–3.91
	″	29–43 cm	–	–	–4.22
	Water	0.5 m	–1.4	26.4	–4.40
	″	1 m	–1	27.2	–5.66
	″	1.5 m	–0.8	27.2	–5.13
	″	2 m	–0.6	27.3	–4.48
	″	3 m	–0.5	27.3	–4.51
	″	3.5 m	–0.5	27.4	–4.65
	″	3.8 m	–0.5	27.4	–5.15
	″	5-cm layer above the bottom	–	–	–4.77
2. Trekhtsvetnoe Lake	Water	0.5 m	–0.3	5.2	–10.8
	″	1 m	0.2	5.2	–10.2
	″	1.5 m	1.6	12.7	–7.1
	″	2 m	2.4	15.2	–6.2
	″	2.5 m	3.2	17.1	–5.9
	″	3 m	3.7	19	–5.8
	″	3.5 m	4	19.9	–5.4
	″	4 m	4.3	20.6	–3.6
	″	4.5 m	4.5	21	–3.8
	″	5 m	4.6	21.3	–2.4
	″	5.5 m	4.7	21.6	–1.4
	″	6 m	4.8	21.9	2.1
3. Lake-on-Zelenyi-Cape	Snow	0–12 cm	–	–	–13.59
	Ice	0–7 cm	–	–	–4.00
	″	7–19 cm	–	–	–3.65
	″	19–34 cm	–	–	–2.22
	″	34–38 cm	–	–	–1.41
	Water	1 m	–1.4	28.7	–4.16
	″	2 m	–1.4	28.7	–4.55
	″	3 m	–1.4	28.8	–5.77
	″	4 m	–1.4	28.8	–4.55
	″	4.5 m	–1.4	28.8	–4.30
	″	5 m	–1.4	28.9	–4.01
	″	5.5 m	–0.9	29	–4.13
6. Nizhnee Ershovskoe Lake	Snow	0–12 cm	–	–	–14.0
	Ice	0–9 cm	–	–	–14.9
	″	9–20 cm	–	–	–13.2
	Water	0.5 m	–0.4	1	–11.7
	″	0.75 m	–	–	–8.9
	″	1 m	2.4	16.4	–6.6

Table 2. (Contd.)

Station no. and location (as indicated in Fig. 1)	Sample	Sampling layer	*T*, °C	*S*, psu	$\delta^{18}O$, ‰
7. Verkhnee Ershovskoe Lake	Snow	0–12 cm	–	–	–14.46
	"	13–24 cm	–	–	–20.12
	Snow crust	12–13 cm	–	–	–15.50
	Snow	24–35 cm	–	–	–21.24
	Ice	0–17 cm	–	–	–13.93
	"	17–37 cm	–	–	–8.91
	Water	0.5 m	0.2	0	–11.3
	"	1 m	1.5	0	–12.1
	"	1.5 m	2.3	0	–12.3
	"	2 m	2.9	0	–11.4
8. Ermolinskaya Inlet	Snow	0–2 cm	–	–	–12.9
	Ice	0–8 cm	–	–	–5.2
	"	8–19 cm	–	–	–5.4
	"	19–49 cm	–	–	–3
	"	49–53 cm	–	–	–2.3
	Water	0.6 m	–	–	–4.1
	"	1.1 m	–	–	–3.4
	"	5-cm layer above the bottom	–	–	–4.3
10. WSBS MSU peer	Snow	0–2 cm	–	–	–11.8
	"	2–3 cm	–	–	–12.7
	"	3–21 cm	–	–	–16

ice and snow $\delta^{18}O$ were about –14‰. Deeper, where the freshwater dominates, the values of $\delta^{18}O$ were the lowest and varied insignificantly from –12.3 to –11.3‰ disregarding the water depth and temperature. This freshwater lake was not affected by seawater and was not stratified according to the isotope profile.

The lake ice was characterized by a $\delta^{18}O$ range from –13.9‰ to –8.9‰ (Table 2), which evidenced the dominating role of atmospheric precipitation in the formation of ice [15] higher $\delta^{18}O$ (–8.9‰) resulted from fractionating during ice formation usually about 3‰ [14]. The snow that covered the ice was characterized by a $\delta^{18}O$ range of –14.5 to –21.2‰.

A heavy oxygen isotope composition was registered in the water of Ermolinskaya Inlet, where it ranged from –3.4‰ to –4.3‰ (Table 2); i.e., the whole water volume had a sea origin. The ice was characterized bya $\delta^{18}O$ range of –5.4 to –2.3‰, and the concentration of the heavy isotopes increased gradually from the ice top to the lower side (Table 2). This was also a result of ice formation from the seawater. The relatively light isotopic composition of the top layer of the ice evidenced the presence of snow in the ice.

Therefore, we conclude that applying the values of $\delta^{18}O$ and profiles of temperature and salinity may be an effective method in defining the water sources feeding water bodies isolated from the sea environment.

In winter of 2011–2012, when the seawater inflow was extremely high due to strong winds, the perturbation of meromictic stratification and significant increase of the water salinity occurred in the water bodies located close to the shoreline of the Karelian Coast of the White Sea.

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REFERENCES

1. A. P. Lisitsyn, in *System of the White Sea.* Vol. 1. *Environment of the White Sea Watershed Area* (Nauchnyi Mir, Moscow, 2010), pp. 353–445 [in Russian].
2. V. V. Kol'ka, O. P. Korsakova, T. S. Shelekhova, et al., Doklady Earth Sciences **442** (1), 139–143 (2012).
3. F. A. Romanenko and O. S. Shilova, Doklady Earth Sciences **442** (2), 242–246 (2012).
4. D. A. Subetto, V. P. Shevchenko, A. V. Ludikova, et al., Doklady Earth Sciences **446** (1), 1042–1048 (2012).
5. A. J. Long, S. A. Woodroffe, D. H. Roberts, and S. Dawson, Quatern. Sci. Revs. **30**, 3748–3768 (2011).
6. A. N. Pantyulin and E. D. Krasnova, in *Proceedings of XIX Intl. Sci. Conf. (School) on Marine Geology* (GEOS, Moscow, 2011), Vol. 3, pp. 241–245 [in Russian].
7. A. G. Degermendzhy, V. M. Belolipetsky, T. A. Zotina, and R. Gulati, Aquat. Ecol **36** (2) (2002).
8. A. S. Savvichev, I. I. Rusanov, D. Yu. Rogozin, et al., Mikrobiology **74** (4), 477–485 (2005).
9. P. V. Belolipetskii, V. M. Belolipetskii, S. N. Genova, and W. M. Mooij, Aquat. Ecol **44**, 561–570 (2010).
10. A. G. Degermendzhi and D. Yu. Rogozin, in *Role of Microorganisms in Functioning of the Living Systems: Fundamental Problems and Bioengineering Outcomes* (Izd-vo SO RAN, Novosibirsk, 2010), pp. 102–104 [in Russian].
11. P. Page, M. Ouellet, C. Hillaire-Marcel, and M. Dickman, Limnol. Oceanogr. **29** (3), 564–573 (1984).
12. M. O. Jeffries, H. R. Krouse, M. A. Shakur, and S. A. Harris, Can. J. Earth Sci. **21**, 1008–1017 (1984).
13. Yu. K. Vasil'chuk, *Isotope Ratios in the Environment. Part 2. Stable Isotope Geochemistry of Massive Ice* (Moscow University Press, Moscow, 2012), Vol. I [in Russian].
14. Yu. K. Vasil'chuk and A. C. Vasil'chuk, *Isotope Ratios in the Environment. Part 1. Stable Isotope Geochemistry of Natural Ice* (Moscow University Press, Moscow, 2011) [in Russian].
15. S. I. Shaporenko, G. A. Korneeva, A. N. Pantyulin, and N. M. Pertsova, Vodn. Resur. **32** (5), 517–532 (2005).