ISSN 0016-7029, Geochemistry International, 2017, Vol. 55, No. 11, pp. 1022–1032. © Pleiades Publishing, Ltd., 2017.
Original Russian Text © E.O. Dubinina, S.A. Kossova, A.Yu. Miroshnikov, N.M. Kokryatskaya, 2017, published in Geokhimiya, 2017, No. 11, pp. 1041–1052.

Isotope (δD, $\delta^{18}O$) Systematics in Waters of the Russian Arctic Seas

E. O. Dubinina[a], *, S. A. Kossova[a], A. Yu. Miroshnikov[a], and N. M. Kokryatskaya[b]

[a] *Institute of Geology of Ore Deposits, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences, Moscow, 119017 Russia*

[b] *Federal Center for Integrated Arctic Research, Russian Academy of Sciences, Arkhangelsk, 163000 Russia*

**e-mail:elenadelta@gmail.com*

Received March 1, 2017; in final form, March 28, 2017

Abstract—Oxygen and hydrogen isotope analysis was performed to study the processes of distribution of water masses and modification of their salinity in the Russian Arctic seas. A wealth of new isotopic data was obtained for freshwater (river runoff, Novaya Zemlya glaciers) and seawater samples collected along a set of extended 2D profiles in the Barents, Kara, and Laptev Seas. The study presents the first δD values measured for the Northeast Atlantic Deep Water NEADW dominated the water column of the Barents Sea ($S = 34.90 \pm 0.05$, $\delta D = +1.55 \pm 0.4‰$, $\delta^{18}O = +0.26 \pm 0.1‰$, $n = 44$). This water mass is present in the Kara Sea and western Laptev Sea. The relationship between δD, $\delta^{18}O$, and salinity data was used to calculate the fractions of waters of different origin, including the fractions of continental runoff in waters of the Barents, Kara, and Laptev Seas. It was shown that the relationships between the isotopic parameters (δD, $\delta^{18}O$) and salinity in waters of the Kara and Laptev Seas is controlled by the intensity of continental runoff and sea ice processes. Sea ice formation is the main factor controlling the formation of the water column on the Laptev Sea shelf, whereas the surface waters of the middle Kara Sea are dominated by the contribution of river runoff. A very strong stratification in the Kara Sea is caused by the presence of a relatively fresh surface layer mostly contributed by estuarine water inputs from the Ob and Yenisei Rivers. The contribution of river waters reaches 40–60% in the surface layer in the central part of the sea and decreases to a few percent down 100 m water depth. Stratification in the western part of the Laptev Sea is controlled by the contribution of freshwater input from the Lena River and modification of salinity by sea ice formation.

Keywords: oxygen and hydrogen isotopes, salinity, seawater, the Arctic, Kara Sea, Laptev Sea, Barents Sea, freshening, continental runoff

DOI: 10.1134/S0016702917110052

INTRODUCTION

Despite the evolving knowledge of the Arctic Ocean, the mechanisms behind the formation and circulation of its water mass remain unclear (Aagard et al., 1981; Bonish and Schlosser, 1995; Dickson and Brown 1994; Jones et al., 1995; Mysak et al., 1993; Peterson, 1989). The Arctic seas receive approximately 10% of the global river runoff (Dittmar and Kattner, 2003; Gordeev et al., 1996). Considerable freshening of the Siberian shelf seas leads to an increase in stratification and a decrease in primary production (Zatsepin, 2010; Flint and Poyarkov, 2015). Primary production in the Arctic is likely to be affected by other environmental factors such as a decrease in nutrient concentrations due to fresh-water dilution, as was observed for Bering Sea continental shelf surface waters (Cooper et al., 1997).

Continental runoff has a significant impact on the ecology of Arctic seas. Since discharge from rivers represents a potential (in some cases actual) source of anthropogenic radionuclide contamination (Pavlov and Pfirman, 1995), quantitative estimation of water depths, river flow direction and distance is of critical importance.

A long-lasting freshening of Arctic seas was documented indirectly by past and present-day stable oxygen isotope profiles from biogenic carbonates (Erlenkeuser et al., 1999; Mueller-Lupp et al., 2003; Schone et al., 2004; Simstich et al., 2004, 2005). For example, the $\delta^{18}O$ values of bivalve shells record the maximum freshening trend in the Kara Sea during the 1990s (Simstich et al., 2005), while seasonal variations in the riverine freshwater discharge were documented for the Laptev Sea (Mueller-Lupp et al., 2003). The oxygen isotopic composition of carbonates reflect the isotopic composition and temperature of the seawater in which the shell calcifies, but it cannot be used to determine sources of freshwater input and reconstruct the structure of the water column, i.e., water-column dynamics.

The stable isotope composition of oxygen and hydrogen in the water molecule is a valuable natural tracer for the determination of the origin and movement of water masses in sea basins. In the Arctic region, where the processes of evaporation play a subordinate role, the relationship δ^{18}O, δD and salinity can be used to determine the origin of the freshwater input to seawaters, e.g., regional atmospheric precipitation and riverine freshwater discharge (Bauch et al., 2012; Bauch et al., 2005; Gordeev et al., 1996; Redfield and Friedman, 1969). Inventory values of river water can be derived for northern Eurasia, because river water δD and δ^{18}O decrease gradually from west to east, which can be explained by the Atlantic air mass flowing up over the continent and causing increased precipitation in this direction (Bauch et al., 2011, Brezgunov et al., 1983).

The stable isotopic composition of water is used as an indicator for water mixing processes and their variation during sea ice freezing and melting. A sharp change in salinity and small values of the isotope fractionation factors between ice and water (Lehmann and Siegenthaler, 1991) results in the transformation of the isotopic composition—salinity relationships. These processes are observed over Arctic shelf areas with shallow water depth, low levels of mixing, and high rates of freezing. The transformation of the isotopic composition—salinity relationships typical of a two-component mixing can be described in part using a third component, sea ice meltwater fraction (Bauch et al., 2003, 2005, 2011–2014).

Studies of oxygen and hydrogen isotope variations in ocean water began in the second half of the 20th century (Dansgaard, 1964; Craig and Gordon, 1965). Later, the discovery of differences in δ^{18}O values of the river water, sea ice meltwater and deep oceanic currents resulted later in the systematic collection of data on Arctic seas (Ostlund and Hut, 1984). In the Russian sector of the Arctic Ocean, studies were conducted in the Bering and Chukchi Seas (Cooper et al., 1997), Laptev and Kara Seas (Bauch et al., 2011–2014). Only scarce data are available for the northern river estuaries (Cooper et al., 2008; Bauch et al., 2013). Existing isotope data sets mainly include oxygen isotope ratios in a water system, while no systematic data are yet available on the hydrogen isotopic composition of the Arctic seas. The accuracy of current methods allows the precise and simultaneous measurements of oxygen and hydrogen stable isotopes in water molecules, which can be used to study the dynamics of seawater exhibiting small variations in δ^{18}O and δD values (Dubinin and Dubinina, 2014; Dubinin et al., 2014). A combination of data from two isotopic systems allows us to reliably constrain the source and genesis of water masses.

This study was performed using high-precision isotope analysis and real-time CTD measurements of hydrophysic parameters such as water temperature and salinity. The purpose of this study is to examine the isotope systematics of seawater and freshwater components in the region, to obtain quantitative estimates of component mixing proportions, and to determine the key factors that influence the isotopic composition and salinity of seawater in the Barents, Kara, and Laptev Seas.

These seas are characterized by different degrees of freshening and ice formation (Aagard and Carmack, 1989). In the Barents Sea, the isotope vs. salinity signature of the North Atlantic water exhibits the lowest degree of modification compared to the Kara and Laptev Seas (Schauer et al., 2002). The Kara Sea receiving about one third of the continental runoff from the Siberian rivers of Eurasia is characterized by the highest inputs of freshwater (Hanzlick and Aagard, 1980, Gordeev et al., 1996). In the Laptev Sea, the isotope (δD, δ^{18}O) vs. salinity signature most likely reflects sea-ice formation (Redfield and Friedman, 1969).

MATERIALS AND METHODS

Samples for isotope analysis were collected on three Arctic expeditions with R/Vs Professor Molchanov (2012, Barents Sea), Professor Shtokman (2014, Kara Sea) and Akademik Mstislav Keldysh (2015, Kara and Laptev Seas). The locations of sampling profiles are shown in Fig. 1. Water samples were collected using a rosette of Niskin sampling bottles to obtain the vertical profiles of hydrographic parameters and δD and δ^{18}O values.

Oxygen isotopes of seawater were analyzed by CO_2—water isotope equilibration technique on a Gas Bench II unit coupled to a PAL autosampler. 0.5 cm^3 samples of seawater were analyzed at 32°C for 18 hours. Oxygen isotopes were analyzed by CF IRMS on a DELTA V+ mass spectrometer (Thermo, Finnigan). Because analyses were performed on seawater samples with a salinity of 3.5%m, they were checked for the presence or absence of significant salt effect (Truesdell, 1974; Horita et al., 1993a, 1993b). Before measuring the δ^{18}O value of seawater, pure dry NaCl crystals and a deionized water standard were mixed to make 0–20 wt % NaCl solutions at a 1% concentration increment, and the mixtures were measured for oxygen isotope composition. This calibration is performed routinely with fresh solutions. Repetitive analyses of calibration standards shows that the applied method has no salt effect in the range of concentrations from 0 to 10%, which well within the salinity range of seawater samples analyzed.

Hydrogen isotope analysis was performed on seawater microsamples (0.001 cm^3) via hot (800°C) chromium reduction by DI IRMS on a DELTAplus mass spectrometer (Thermo, Finnigan). The δD and δ^{18}O values are given relative to the V-SMOW and V-SLAP international standards. The measurement precision for δ^{18}O and δD analyses was ±0.1 and ±0.3‰, respectively.

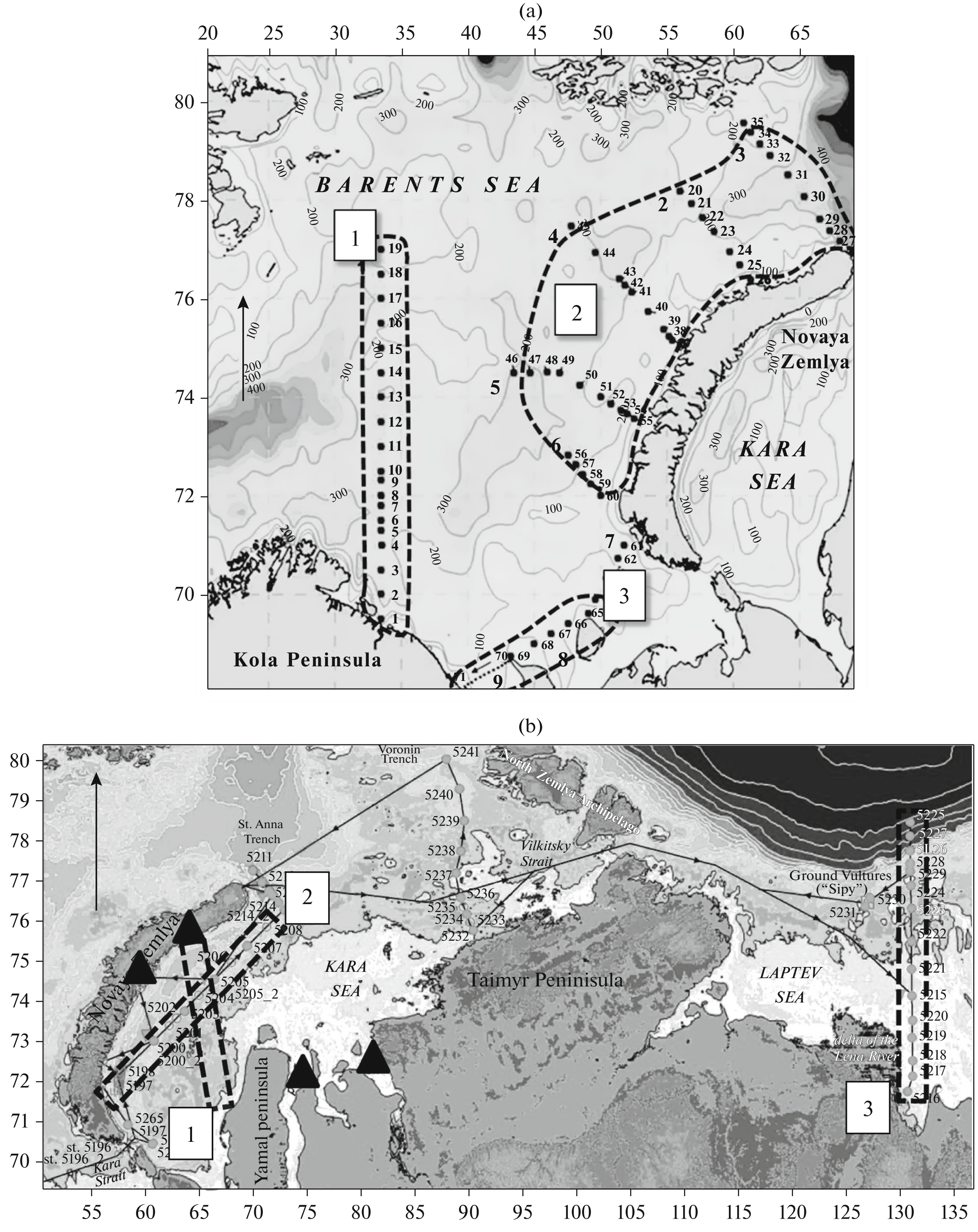

Fig. 1. Scheme of sampling profiles: (a) Barents Sea: 1—Kola meridian, 2—a group of profiles northwest of Novaya Zemlya Archipelago (Novaya Zemlya profiles), 3—profile across the White Sea Gorge; (b) Kara and Laptev Seas: 1—Yamal profile (2014), 2—Novaya Zemlya and 3—Lena profiles (2015). The positions of stations sampled for river and glacier waters are shown by triangles (2014).

Table 1. Isotopic characteristics of Barents Sea waters

Type of water	n	S ± (1σ)	δ^{18}O ± (1σ)	δD ± (1σ)
All samples of Barents seawater collected at >5 m water depth	119	34.56 ± 0.38	+0.18 ± 0.18	+0.79 ± 1.02
Minimum		33.20	–0.34	–3.0
Maximum		34.96	+0.57	+2.2
Waters with maximal salinity collected along the Kola meridian	21	34.36 ± 0.02	+0.16 ± 0.11	+0.86 ± 0.23
Waters with NEADW-like isotopic parameters	44	34.90 ± 0.04	+0.26 ± 0.10	+1.55 ± 0.38

RESULTS AND DISCUSSION

Barents Sea

Water samples were studied in the Barents Sea along the meridional profile of stations named as the Kola meridian, extending from the Kola Peninsula across the White Sea Gorge and five profiles trending in the N—W direction from Novaya Zemlya Archipelago (Fig. 1a). The homogeneous isotopic versus salinity signature indicates the weakly stratified water column of the Barents Sea. Table 1 shows averaged isotope data for the seawaters from the Barents Sea. All water samples collected at depths of more than 5 m have a narrow salinity range (S = 33.20–34.96), while the differences in the oxygen and hydrogen isotope values are 0.9 and 5.2‰, respectively (Table 1).

The δ^{18}O/salinity relationship (Fig. 2a) shows a well-defined North Atlantic mixing line for our data, suggesting that North Atlantic water inflow is the likely source of Barents Sea waters (Craig, Gordon, 1965). On this plot, all samples fall in two distinct fields: waters sampled along the Kola meridian profile (S = 34.36 ± 0.02) and waters sampled along profiles located NW of Novaya Zemlya (S = 34.85 ± 0.09). These two water masses have different isotopic parameters. The first one is characterized by slightly lighter oxygen and hydrogen isotopic compositions, but both types of samples cluster along a global mixing line. The lighter isotopic composition of waters collected along the Kola meridian profile can be explained by freshening. The δ^{18}D/salinity correlation (Fig. 2b) confirms this conclusion and suggests that a sea-ice meltwater component may be an additional factor transforming a salinity profile of Kola meridian waters (arrow B in Fig. 2b). A strong isotope versus salinity correlation shows that the Kola meridian waters can be regarded as a separate water mass with homogeneous isotopic and hydrophysical parameters (Table 1). These waters may be influenced by the Norway Coastal Current (NCC), flowing eastward through the Barents Sea (Schauer et al., 2002), whereas their homogeneous isotopic vs. salinity signature may result from the effective mixing along the Kola meridian profile.

Freshening of Barents Sea waters is most evident along the White Sea Gorge profile where waters have a salinity of not less than 30‰. In addition to a water inflow through the White Sea Gorge, the influx of freshwater is observed in direct proximity to the Kola Peninsula shoreline and disappears a few tens kilometers offshore. Nevertheless, both sources of freshwater input are clearly seen on the δD/salinity correlation plot (Fig. 2b).

Barents Sea waters northwest of Novaya Zemlya are dominated by a well-defined water mass with a maximum salinity and extremely stable isotopic values, which show variation within the analytical error. Forty four samples have a salinity of 34.90 ± 0.04, and δ^{18}O and δD of +0.26 ± 0.10 and +1.55 ± 0.38‰, respectively. Based on their salinity range and oxygen isotope values, they correspond to the Northeast Atlantic Deep Water (NEADW) (Frew et al., 2000). Therefore, the isotopic values measured in these waters can be regarded typical of the NEADW.

Kara Sea

Freshening of the Kara Sea was studied using observations from two cruises in August—September 2014 and 2015. The 2014 cruise data were obtained on the submeridional profile from the Yamal peninsula to Blagopoluchiya Bay of Novaya Zemlya Archipelago (hereinafter referred to as the Yamal profile). The 2015 cruise data were obtained on the profile across the Kara Sea along Novaya Zemlya (hereinafter referred to as the Novaya Zemlya profile). The locations of sampling profiles are shown in Fig. 1b. Data on the Yamal profile, estuarine waters of the Ob and Yenisei Rivers, and Novaya Zemlya glaciers reflect a strong stratification in the Kara Sea due to supply of fresh surface water from the Ob and Yenisei Rivers (Dubinina et al., 2017). For the Yamal profile, we calculated a two-component mixing model describing a Barents-derived seawater component (NEADW) and a freshwater component, whose isotopic parameters were obtained by extrapolating to S = 0 (Table 2). As seen in Table 2, the oxygen isotope composition of this freshwater component is close to that of Ob waters. The fractions of river water (x) in each sample analyzed were quantified by applying a mass balance calculation:

$$\delta_{\text{var.}} = x\delta_{\text{rw}} + (1 - x)\delta_{\text{sw}},$$

where $\delta_{\text{var.}}$, δ_{rw} and δ_{sw} are the measured hydrogen (or oxygen) isotopic compositions of river water and seawater components, respectively. The data from Table 2

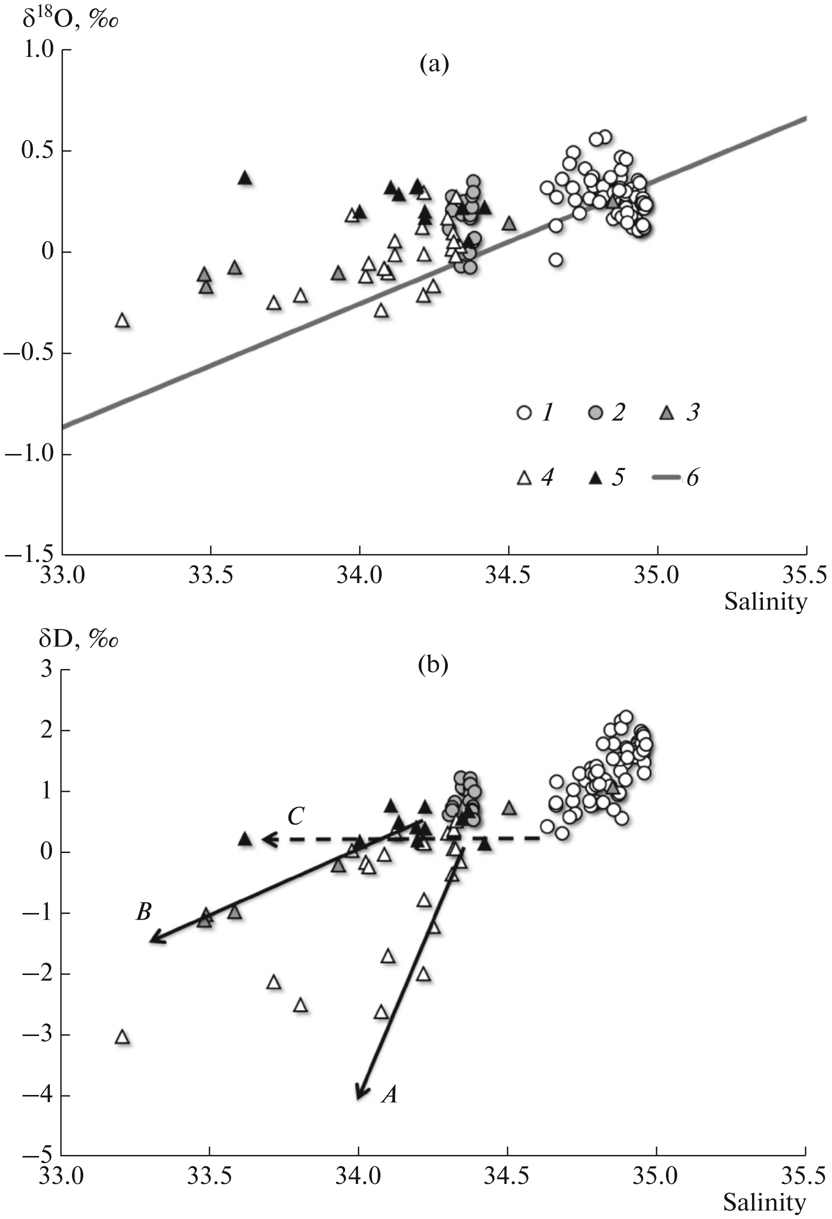

Fig. 2. The isotopic composition versus salinity plots for Barents Sea waters: *1*—high-salinity waters (S > 34.5) along the Novaya Zemlya profiles, *2*—high-salinity waters (S > 34.3) along the Kola meridian. Low-salinity waters: *3*—in the vicinity of the Kola meridian, *4*—White Sea Gorge, *5*—Novaya Zemlya profiles; *6*—global North Atlantic mixing line (Craig and Gordon, 1965). Arrows (b) show the trends defined by mixing with waters of the White Sea (A), runoff from the Kola Peninsula (B), and sea-ice meltwater (C).

are used for the mixing endmembers. The calculated fractions of river water in the water column along the Yamal profile are 5–10% in the main part of the water column and less than 5% at depths more than 100 m. The calculated fractions of river water are highest (over 40%) in the thin (not greater than 15–20 m) surface layer in the central part of the sea. The distribution of river water fractions in the water column along the Yamal profile (2014) is shown in Fig. 3a. Similar calculations for the Novaya Zemlya profile (2015) using a mode of two-component mixing between NEADW and river runoff are shown in Fig. 3b. The isotopic parameters calculated for the freshwater component along the Novaya Zemlya profile by extrapolating to S = 0 (Table 2) are close to those of freshwater from the Ob and Yenisei Rivers.

Therefore, freshening of the surface layer in the central part of the Kara Sea clearly results from contributions of river waters. The river water fractions calculated for different years are shown to the almost identical along different profiles. Both profiles are charac-

Table 2. Isotopic characteristics of fresh and modified waters

Component	Year of sampling	δD, ‰	δ^{18}O, ‰
Yenisei, estuary (Dubinina et al., 2017)	2014	–134	–17.7
Yenisei (Bauch et al., 2005)	2000–2001	nd	–17.0
Yenisei (Bauch et al., 2003)	1999	nd	–18.1
Yenisei (Brezgunov et al., 1983)	1977, 1976	nd	–17.0; –18.2
Yenisei (Cooper et al., 2008)	2003–2006	nd	–18.4
Ob (Bauch et al., 2005)	2000–2001	nd	–15.7; –16.1
Ob (Bauch et al., 2003)	1999	nd	–16.8
Ob (Brezgunov et al., 1983)	1977	nd	–14.6; –15.9
Ob (Brezgunov et al., 1983)	1976	nd	–16.2
Ob (Cooper et al., 2008), averaged runoff	2003–2006	nd	–14.9
Lena (this study), calculated to S = 0	2015	–144	–19.0
Lena (Letolle et al., 1993)	1989	nd	–19.6
Lena (Muller-Lupp et al., 2003)	1994	nd	–18.7
Lena (Bauch et al., 2010)	2007	nd	–19.8
Lena (Cooper et al., 2008), average river runoff	2003–2006	nd	–20.5
Novaya Zemlya glaciers, Serp i Molot, Rose (Dubinina et al., 2017)	2014	–94...–123	–13.4...–17.0
Freshwater component transported from the White Sea Gorge to the Barents Sea (this study), S = 0	2012	–112	–15.4
Freshwater component from the Kola Peninsula to the Barents Sea (this study), S = 0	2012	–56	–9.4
Freshwater component in the center of the Kara Sea, Yamal profile (this study), S = 0	2014	–119.4	–15.5
Freshwater component in the center of the Kara Sea, Novaya Zemlya profile (this study), S = 0	2015	–129	–16.8
Freshwater component on continental slope, Laptev Sea, 130° E (this study), S = 0	2015	–173	–23
Water with modified salinity (S = 33–34.5), Laptev shelf, 130° E (this study)	2015	–0.9...–21	–2.6...0.1

terized by strong stratification of the water column and the presence of the freshened surface layer covering the entire central part of the sea. This layer is likely to be similar to a low-salinity zone, which was detected in the southwestern part of the Kara Sea (Zatsepin et al., 2010). It was shown that this low-salinity (S < 25) zone has an area of 40,000 km^2, while the estimated dissolved silica content, alkalinity and salinity suggest that river water supply from the Yenisei River is the main source of the freshwater component. These researchers suggest that this freshened surface layer was formed as a result of a widespread river flood and wind-driven transport of river water to the western part of the sea. However, our data show that freshened zones in surface layer due to river contributions are common and can be regarded as characteristic of the Kara Sea.

The location of the Novaya Zemlya profile (Fig. 1b) shows that the river plume from the Ob and Yenisei River estuaries spreads over most of the sea surface, reaching Novaya Zemlya. As with water samples along the Yamal profile, the isotopic parameters of waters of the Novaya Zemlya profile are markedly different from those of saline NEADW. The highest river water fraction along the Novaya Zemlya profile reaches 60% in the surface layer and significantly decreases (up to a few percent, but not to zero) with depth.

Laptev Sea

Water samples were studied in the Laptev Sea along a nearly N–S profile stretching from the Lena River delta front across the entire shelf and a part of the continental slope (Lena profile, Fig. 1b). The influence of freshwater supply from the Lena River on the composition of Laptev Sea waters is of particular interest in terms of freshening of the Arctic basin. However, our results show that the situation in this sea is far more

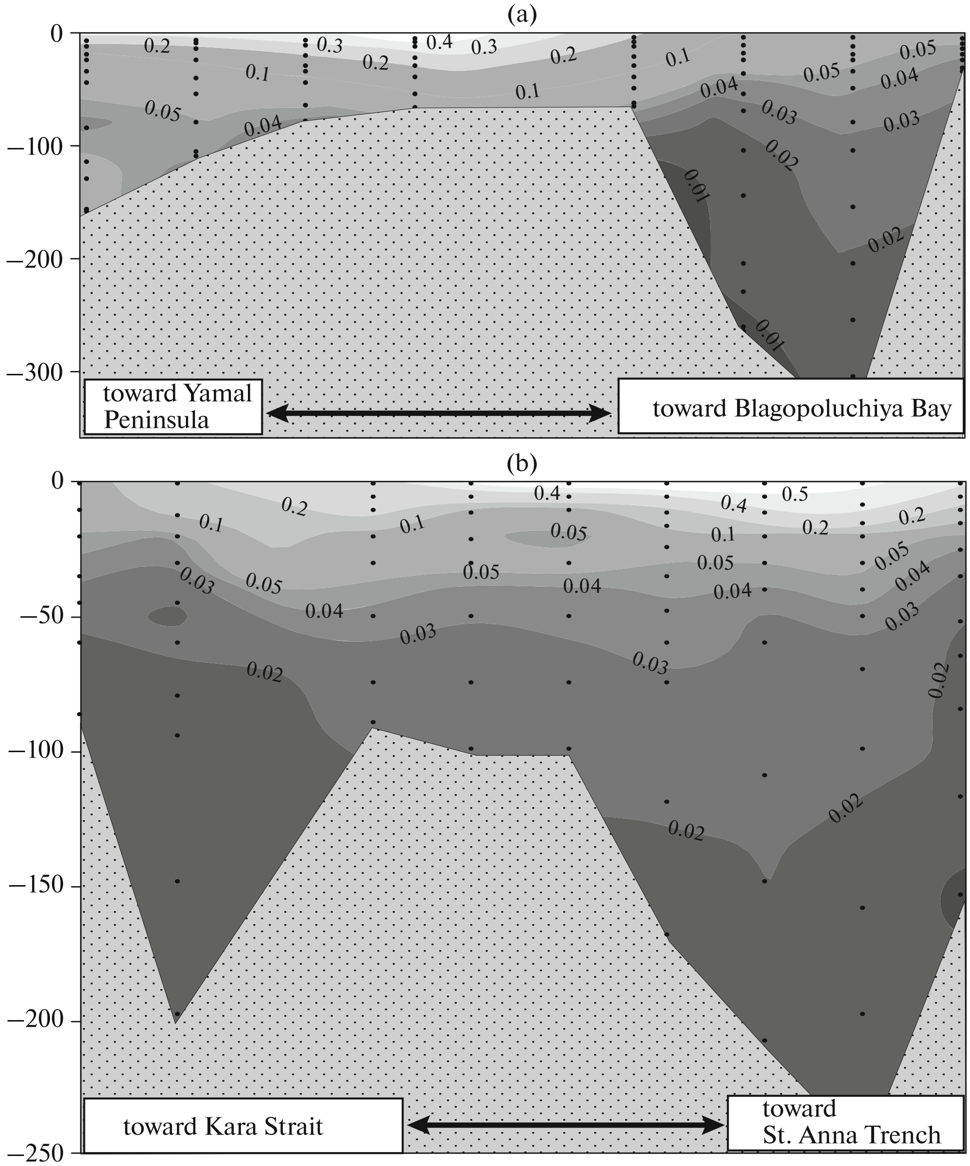

Fig. 3. Spatial distribution of the freshwater river component in Kara Sea waters: (a) Yamal profile, sampling period—August 2014, (b) Novaya Zemlya profile, sampling period—August 2015. Numbers on the *y*-axis denote water depths (m), numbers on profiles denote the river water fractions. The calculations were performed using a two-component mixing model for high-salinity Barents Sea waters and freshwaters from the Yenisei and Ob Rivers.

complex than a simple freshening due to an increasing fraction of river water. The δD/salinity plot (Fig. 4) for the Lena profile shows that the compositions of seawater are influenced not only by mixing processes, but also sea-ice formation. The entire Lena profile can be conditionally divided into shelf and continental slope zones.

A distinctive feature of shelf waters is a strong stratification of the water column in terms of salinity and oxygen and hydrogen isotopic composition. Surface waters at most stations near the river mouth are clearly influenced by discharge of the Lena River (field A, Fig. 4). This zone is characterized by a strong freshening and a decrease in salinity to 3‰ in proximity to the river mouth, while the oxygen and hydrogen isotope composition of desalinated waters is similar to the equilibrium composition of river waters and sea ice (Fig. 4). Extrapolation to zero salinity shows that the average isotopic parameters of the freshwater contribution from the Lena River are $\delta^{18}O = -19$ and $\delta D = -144‰$. This averaged $\delta^{18}O$ value is close to some results of previous surveys (from −18.7 to −19.8‰, Letolle et al., 1993; Muller-Lupp et al., 2003, Bauch et al., 2010). The calculated isotopic parameters ($\delta^{18}O$ and δD) can be regarded to be characteristic values for Lena estuarine waters. Our results disagree with averaged estimates (Cooper et al., 2008) obtained in 2003–2006 (Table 1) probably because of different approaches to the calculation of averaged isotopic values.

Water samples collected along the Lena profile at stations on the continental slope are characterized by markedly different salinity and isotopic values. This zone exhibit insignificant variations with the highest S, δD and δ^{18}O values. The relationship between the isotopic parameters and salinity corresponds, in a first approximation, to the two-component mixing model. Figure 5 shows a δ^{18}O/salinity correlation plot for the Laptev Sea continental slope. Relatively high salinity waters of Barents Sea and a global North Atlantic mixing line are also shown for comparison. The correlation line for stations at the continental slope has the slope of 0.68, which is very close to the same slope of the North Atlantic mixing line (0.61, Graig, Gordon, 1965). The intercept term (δ^{18}O ≈ −23.1‰) of this correlation indicates the contribution of a component with the oxygen isotopic values lower than δ^{18}O = −21‰, which was determined for the global North Atlantic mixing line. This component is likely to be atmospheric precipitation in the Arctic region (δ^{18}O = −23‰, Frew et al., 2000). The extrapolation to zero salinity shows that the δD value of this component is −173‰. The calculated parameters of the freshwater component may represent the averaged composition of precipitations in the Arctic region at 76–78 degrees north latitude, in a zone of the continental slope in the terminal part of the Lena profile. However, the complex structure of the water column in this zone, as indicated by hydrographic data (T—S) suggests contributions of several water masses, including those exported from the shelf zone. This is supported, for example, by the position of the more saline (S > 33) Laptev shelf waters on the δ^{18}O/salinity plot (Fig. 5).

The permanent stratification in the water column on the Laptev Sea shelf appears to be the main factor responsible for the formation of waters with anomalously high salinity relative to the two-component mixing line on the plot of isotopic values versus salinity (field B, Fig. 4). The effects of sea ice formation on the modification of a salinity profile have been reported by previous studies (Bauch et al., 2010; Johnson and Polyakov, 2001). Our data show that these processes influence salinity in the middle part of the profile, from the Lena delta to the continental slope down to 20 m water depth. A distinctive feature of waters modified by salinity changes is a lack of correlation between salinity and their δ^{18}O and δD values. These waters on the Laptev Sea shelf have the following characteristics: relatively high salinity (30–34.5), low temperature (from –0.6 to –1.8°C) and strong variability of their δD and δ^{18}O signatures (Table 2). In the absence of any significant correlation with salinity, variations in δ^{18}O and δD values can be related to sampling depth. Figure 6 shows the vertical distribution of δD values in the bottom layer from the central part of the Lena profile for 15 water samples with nearly identical salinity and temperature (34 ± 0.27 and −1.5 ± 0.3°C). As can be seen, salinity is subject to modification independently of the freshwater fraction and isotopic composition. The presence of modified waters with the lowest δD (δ^{18}O) values in the upper water column indicates that the upper layers are most subject to modification, because these isotopically light waters must have the lowest salinities prior to modification. The preservation of the vertical distribution of isotopic parameters in waters modified by salinity changes is indicative of a very strong stratification in the the Laptev Sea shelf.

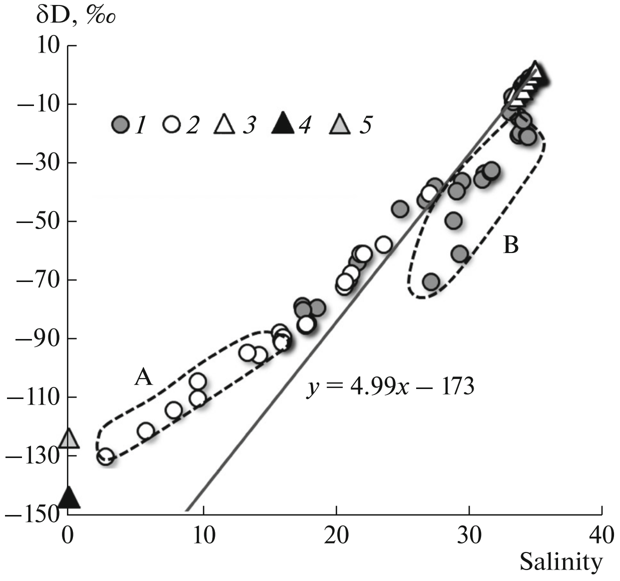

Fig. 4. The δD versus salinity plot for the Lena profile: *1*—shelf waters (5–45 m), *2*—surface waters (0–5 m) in the shelf zone, *3*—continental slope, *4*—Lena River water (extrapolated to zero salinity), *5*—sea ice in equilibrium with Lena River water (calculated after Lehmann and Siegenthaler, 1991). Fields: A—mixing with freshwater from the Lena River and sea-ice meltwater, B—waters with modified salinity on the shelf zone. A linear correlation is made for Continental slope waters.

CONCLUSIONS

This study provides the first systematic data on water masses of the Barents, Kara, and Laptev Seas (Tables 1 and 2). The isotopic composition, hydrographic regime, and structure of the water column of the Arctic seas are controlled by two major factors: a mixing of water masses and modification of salinity by sea ice formation. The relationship between these two factors predetermines the isotopic signatures and the structure of the water column along the studied profiles. Waters of the Barents Sea are characterized by an apparent lack of stratification, i.e., the homogeneous δD, δ^{18}O/ salinity signature. The Barents Sea hydrology is dominated by the contribution of the Northeast

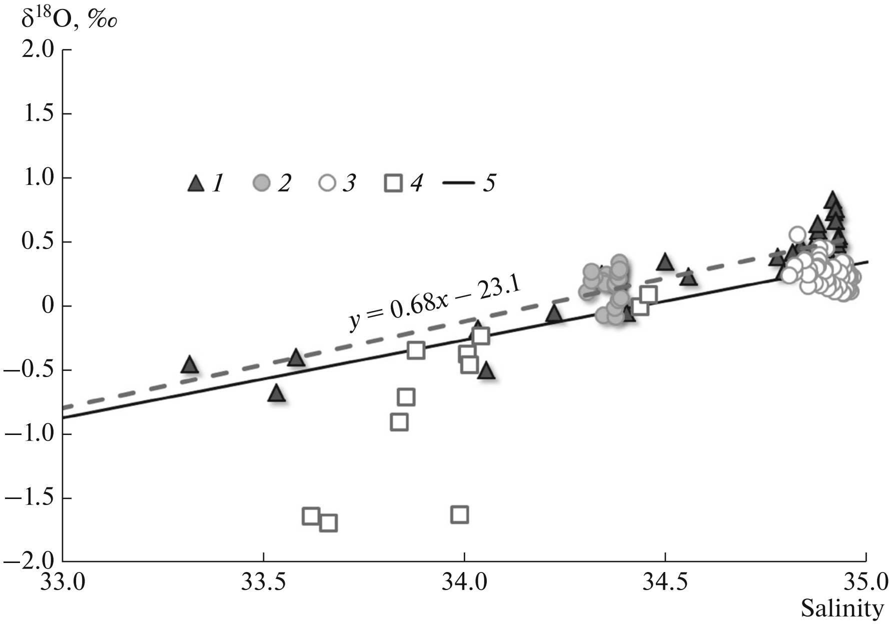

Fig. 5. The $\delta^{18}O$ versus salinity plot: *1*—waters of the Laptev Sea continental slope, *2*—high-salinity waters (S > 34.3) along the Kola meridian, *3*—NEADW-derived component in the Barents Sea (S > 34.90 ± 0.05), *4*—Laptev Sea shelf waters with salinity above 33‰, *5*—global North Atlantic mixing line with $\delta^{18}O = 0.61S–21$ (Craig and Gordon, 1965). A dashed line denotes a linear correlation for waters of the Laptev Sea continental slope at 130 E.

Atlantic Deep Water (NEADW) for which the hydrogen isotopic signature was first determined in this study. The NEADW is the major component in the water column of Barents Sea and can be thus considered as the main source of "marine" water masses in the Kara and Laptev Seas.

The Kara Sea is characterized by a widespread freshening due to an increasing fraction of continental river runoff from the Ob Bay and Yenisei Gulf. The geographic location of the Kara Sea and its isolation from the Atlantic water masses circulating in the Arctic are the main factors responsible for the long-term freshening and permanent stratification of the waters in the central part of the sea. The contribution of river freshwaters in the middle Kara Sea may reach 40–60% and is not equal to zero in waters of the Novaya Zemlya depression. Laptev Sea shelf waters are also characterized by a strong stratification. Their isotopic parameters are controlled to some degree by mixing with freshwaters from the Lena River and local precipitation, as well as by the transformation of salinity due to the winter sea ice formation. The preservation of the stratified water column on the Laptev Sea shelf is probably controlled by a weak wind-driven vertical mixing and slow water exchange with the adjacent Arctic seas.

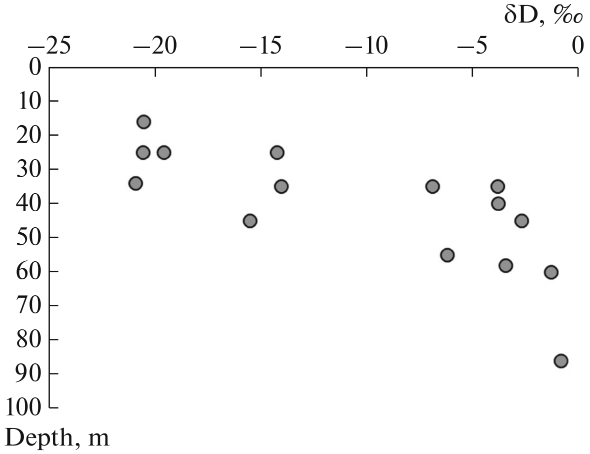

Fig. 6. The vertical distribution of δD values in waters modified by salinity changes (field B in Fig. 4) on the Laptev Sea shelf.

ACKNOWLEDGMENTS

The authors thank the crews on the research vessels Professor Molchanov, Professor Shtokman, and Akademik Mstislav Keldysh. We also thank M.V. Flint and all members of the expeditions during which the materials used in this study were collected.

REFERENCES

K. Aagard, L. K. Coachman, and E. Carmack, "On the halocline of the Arctic Ocean," Prog. Oceanography, **28** (6), 529–545 (1981).

K. Aagard, "The role of sea ice and other fresh water in the Arctic Circulation," J. Geophys. Res. **94** (10), 14485–14498 (1989).

D. Bauch, H. Erlenkeuser, and N. Andersen, "Water mass processes on Arctic shelves as revealed from ^{18}O of H_2O," Glob. Planet. Change, **48**, 165–174 (2005).

D. Bauch, H. Erlenkeuser, V. Stanovoy, et al., "Freshwater distribution and brine waters in the southern Kara Sea in summer 1999 as depicted by $\delta^{18}O$ results," in *Siberian River Run-Off in the Kara Sea,* Ed. by R. Stein , (Elsevier, Amsterdam, 2003), pp. 73–90.

D. Bauch, J. Hölemann, S. Willmes, M. Gröger, A. Novikhin, A. Nikulina, H. Kassens, and L. Timokhov, "Changes in distribution of brine waters on the Laptev Sea shelf in 2007," J. Geophys. Res. **115**, C11008 (2010).

D. Bauch, M. Groger, I. Dmitrenko, J. Holemann, et al., "Atmospheric controlled freshwater release at the Laptev Sea continental margin," Polar Res. **30,** 5858 (2011).

D. Bauch, J. A. Hölemann, I. A. Dmitrenko, et al., "Impact of Siberian coastal polynyas on shelf-derived Arctic Ocean halocline waters," J. Geophys. Res. **117** (2012).

D. Bauch, J. Hölemann, A. Nikitina, C. Wegner, M. Janout, L. A. Timokhov, and H. Kassens, "Correlation of river water and local sea-ice melting on the Laptev Sea shelf (Siberian Arctic)," J. Geophys. Res. **118**, 550–561 (2013).

D. Bauch, S. Torres-Valdes, I. Polyakov, A. Novikhin, I. Dmitrenko, J. McKay, and A. Mix, 'Halocline water modification and along-slope advection at the Laptev Sea continental margin," Ocean Sci. **10**, 141–154 (2014).

G. Bonish and P. Schlosser, "Deep water formation and exchange rates in the Greenland/Norwegian Seas and Eurasian Basin of the Arctic Ocean derived from tracer balances," Prog. Oceanography, **35**, 29–52 (1995).

V. S. Brezgunov, V. K. Debolskii, V. V. Nechaev, et al., "Characteristics of the formation and salinity upon mixing of sea and river waters in the Barentz and Kara Seas," Water Res. **9** (4), 335–344 (1983).

L. W. Cooper, T. E. Whitledge, J. M. Grebmeier, and T. Weingartner, "The nutrient, salinity, and stable oxygen isotope composition of Bering and Chukchi Seas waters in and near the Bering Strait," J. Geophys. Res. **102**, 12563–12573 (1997).

L. W. Cooper, J. W. McClelland, R. M. Holmes, P. A. Raymond, J. J. Gibson, C. K. Guay, and B. J. Peterson, "Flow-weighted values of runoff tracers ($d^{18}O$, DOC, Ba, alkalinity) from the six largest Arctic rivers," Geophys. Res. Lett. **35** (2008).

H. Craig and L. Gordon, "Deuterium and oxygen-18 variations in the ocean and the marine atmosphere," *Stable Isotopes in Oceanographic Studies and Paleotemperatures, Spoletto, Italy,* Ed. by E. V. Tongiogi and E. F. Lishi (CNR, Pisa, 1965), pp. 9–130.

W. Dansgaard, "Sable isotopes in precipitation," *Tellus*, **19**, 435–463 (1964).

R. R. Dickson and J. Brown, "The production of North Atlantic Deep Water: sources, rates, and pathways," J. Geophys. Res. **99**(6), 12319–12341 (1994).

T. Dittmar and G. Kattener, "The biogeochemistry of the river and shelf ecosystem of the Arctic Ocean: a review," Marine Chem. **83**, 103–120 (2003).

A. V. Dubinin and E. O. Dubinina, "Isotope composition of oxygen and hydrogen in the Black Sea waters as a result of the dynamics of water masses," Oceanology **54** (6), 713–729 (2014).

A. V. Dubinin, E. O. Dubinina, T. P. Demidova, N. M. Kokryatskaya, M. N. Rimskaya-Korsakova, S. A. Kossova, and E. V. Yakushev, "Stable isotope evidence for the Bottom Convective Layer homogeneity in the Black Sea,"Geochem.Trans. **15** (3), (2014).

E. O. Dubinina, S. A. Kossova, A. Yu. Miroshnikov and R. V. Fyaizullina, "Isotope parameters (δD, $\delta^{18}O$) and sources of freshwater input to Kara Sea," Oceanology, **57** (1), 31–40 (2017).

B. Ekwurzel, P. Schlosser, R. Mortlock, and R. Fairbanks, "River runoff, sea ice meltwater, and Pacific water distribution and mean residence times in the Arctic Ocean," J. Geophys. Res. **106** (C5), 9075–9092 (2001).

H. Erlenkeuser, R. F. Spielhagen, and E. Taldenkova, "Stable isotopes in modern water and bivalve samples from the southern Kara Sea," Rep. Polar Res. **300**, 80–90 (1999).

M. V. Flint and S. G. Poyarkov, "Comprehensive research on the Kara Sea ecosystem (128th Cruise of research vessel *Professor Shtokman*)," Oceanology, **55** (4), 657–659 (2015).

R. D. Frew, P. F. Dennis, K. J. Heywood, et al., "The oxygen isotope composition of water masses in the northern North Atlantic," Deep-Sea Res. **47**, 2265–2286 (2000).

V. V. Gordeev, J. M. Martin, I. S. Sidorov, and M. V. Sidorova, "A reassessment of the Eurasian river input of water, sediment, major elements, and nutrients to the Arctic Ocean,"Amer. J. Sci. **296**, 664–691 (1996).

D. Hazlick and K. Aagard, "Freshwater and Atlantic water in the Kara Sea," J. Geophys. Res. **85**(9), 4937–4932 (1980).

J. Horita, D. J. Wesolowski, and D. R. Cole, "The activity-composition relationship of oxygen and hydrogen isotopes in aqueous salt solutions: I. Vapor-liquid water equilibration of single salt solutions from 50 to 100°C," Geochim. Cosm. Acta **57**, 2797–2817 (1993a).

J. Horita, D. R. Cole, and D. J. Wesolowski, "The activity-composition relationship of oxygen and hydrogen isotopes in aqueous salt solutions: II. Vapor-liquid water equilibration of mixed salt solutions from 50 to 100°C and geochemical implications," Geochim. Cosmochim. Acta, **57**, 4703–4711 (1993b).

M. A. Johnson and I. V. Polyakov, "The Laptev Sea as a source for recent Arctic Ocean salinity changes," Geophys. Res. Lett. **28** (10), 2017–2020 (2001).

E. P. Jones, B. Rudels, and L. G. Anderson, "Deep water of the Arctic ocean: origins and circulation," Deep-Sea Res. **42** (5), 737–760 (1995).

M. Lehmann and U. Siegenthaler, "Equilibrium oxygen- and hydrogen-isotope fractionation between ice and water," J. Glac. **37**, 23–26 (1991).

R. Létolle, J. Martin, A. Thomas, V. Gordeev, S. Gusarova, and I. Sidorov, "^{18}O abundance and dissolved silicate in the Lena delta and Laptev Sea (Russia)," Marine Chem. **43**, 47–64 (1993).

T. Mueller-Lupp, H. Erlenkeuser, and H. A. Bauch, "Seasonal and interannual variability of Siberian river discharge in the Laptev Sea inferred from stable isotopes in modern bivalves," Boreas **32** (2), 292–303 (2003).

L. A. Mysak, T. F. Stoker, and F. Huang, "Century-scale variability in a randomly forced, two-dimensional thermohaline ocean circulation model," Climate Dynamics **8**, 103–116 (1993).

H. G. Ostlund and G. Hut, "Arctic ocean water mass balance from isotope data," J. Geophys. Res. **89**, 6373–6381 (1984).

V. K. Pavlov and S. L. Pfirman, "Hydrographyc structure and variability of the Kara Sea: Implications for pollutant distribution," Deep-Sea Res. **42** (6), 1369–1390 (1995).

Peterson, R. G. "The Subantarctic and Polar fronts in relection to deep water masses through the southwestern Atlantic," J. Geophys. Res. **94**(8), 10817–10838 (1989).

A. C. Redfield and I. Friedman, "The effect of meteoric water, melt water and brine on the composition of polar sea water and of the deep waters of the ocean," Deep-Sea Res., **16**, 197–214 (1969).

U. Schauer, H. Loeng, B. Rudels, V. K. Ozhigin, and W. Dieek, "Atlantic water flow through the Barents and Kara seas," Deep-Sea Res. **1** (49), 2281–2298 (2002).

B. R. Schone, A. D. Freyre Castro, J. Fiebig, S. D. Houk, W. Oschmann, and I. Kröncke, "Sea surface water temperatures over the period 1884–1983 reconstructed from oxygen isotope ratios of a bivalve mollusk shell (Arctica islandica, southern North Sea)," Palaeogeography, Palaeoclimatology, Palaeoecology **212**, 215–232 (2004).

J. Simstich, V. Stanovoy, D. Bauch, H. Erlenkeuser, and F. Spielhagen, "Holocene variability of bottom water hydrography on the Kara Sea shelf (Siberia) depicted in multiple single-valve analyses of stable isotopes in ostracods," Marine Geol. **206**, 147–164 (2004).

J. Simstich, I. Harms, M. J. Karcher, H. Erlenkeuser, V. Stanovoy, L. Kodina, D. Bauch, and F. Spielhagen, "Recent freshening in the Kara Sea (Siberia) recorded by stable isotopes in Arctic bivalve shells," J. Geophys. Res. **110**, C08006 (2005)

A. H. Truesdell, "Oxygen isotope activities and concentrations in aqueous salt solutions at elevated temperatures: consequences for isotope geochemistry," Earth Planet. Sci. Lett. **23**, 387–396 (1974).

A. G. Zatsepin, P. O. Zavialov, V. V. Kremenetskiy, S. G. Poyarkov, and D. M. Soloviev, "The upper desalinated layer in the Kara Sea," Oceanology, **50** (5), 657–667 (2010).

A. G. Zatsepin, V. V. Kremenetskiy, A. A. Kubryakov, S. V. Stanichny, and D. M. Soloviev, "Propagation and transformation of waters of the surface desalinated layer in the Kara Sea," Oceanology **55** (4), 450–460 (2015).

Translated by N. Kravets