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MARINE PHYSICS

The Upper Desalinated Layer in the Kara Sea

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Abstract—An area of about 40 000 km^2 of desalinated upper layer waters with a salinity of less than 25 psu was found during cruise 54 of the R/V *Akademik Mstislav Keldysh* in the southwestern part of the Kara Sea (September 2007). Close to the boundary of this region located near the eastern coast of Novaya Zemlya, the salinity was less than 16 psu. The thickness of the desalinated layer was about 10 m. The results of the chemical analysis revealed that the observed desalination of the sea water was produced, first of all, by the Yenisei River, while the contribution of the Ob River's waters was secondary. However, the most desalinated region near the eastern coast of Novaya Zemlya was separated from the Ob–Yenisei estuary and corresponded to a quasi-isolated lens. It is likely that the formation of this lens, as well as the major part of the desalinated upper layer waters, occurred in June when the flood of the Yenisei was maximal, while the further drift of the desalinated waters to the west of the Ob–Yenisei estuary was forced by the prevailing northern wind. The additional desalination (by 2–3 psu and even more) of the upper layer waters near the eastern coast of Novaya Zemlya might be related to the melting of the Novozemelskiy ice massif. The regularities of the temporal evolution of the upper desalinated layer, as well as the influence of this layer on the hydrological structure and dynamics of the southwestern Kara Sea, are discussed.

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INTRODUCTION

The river runoff is a major factor of the Kara Sea's hydrology. The two largest Siberian rivers—the Ob and Yenisei—along with smaller rivers, enter the Kara Sea. The catchment area of the Ob and Yenisei rivers measures 5 500 000 km^2, which about 4% of the land surface of the earth [18]. The Kara Sea receives more than half of the river runoff from the Siberian Arctic and more than a third of the total river runoff to the Arctic Ocean [2, 18]. The annual river runoff into the Kara Sea makes up 1100–1300 km^3, of which Ob and Yenisei discharge 400–450 and 600–630 km^3 per year, respectively.

Substantial seasonality is inherent to the river runoff. About 80% of the runoff occurs in the warm season with the peak in June [13]. The interannual runoff variability depending on the precipitation abundance over the catchment area prevails too. Thanks to the huge dimensions of the latter, the total annual river runoff is subjected to lesser variations as compared to the runoff of the individual rivers.

The riverine waters spread in the upper sea layer about 5–15 m in thickness. According to the available estimates [18], desalinated waters are able to occupy up to 40% of the Kara Sea area. The range of the river water penetration into the sea and the configuration of the layer of desalinated waters vary from month to month and from year to year. Depending on the river runoff's volume and, basically, the wind conditions, three types of desalinated waters' propagation occur: the "western," the "central" (or "fan shaped"), and the "eastern" ones [6, 7]. One speaks of the western type when the desalinated waters reach the eastern margin of the Novaya Zemlya Islands. The central type is distinguished by the penetration of desalinated waters far north of the river mouths. The eastern type implies that the riverine waters are held up against the shore by the boundary current and transported to the Severnaya Zemlya Islands and further to the Laptev sea.

Our primary consideration is the description of the spatial expansion and the basic features (the temperature, salinity, density, thickness, area, and volume) of the waters of the surface desalinated layer (SDL) in the southwestern Kara Sea in September–October of 2007 based on the measurement data from the 54th cruise of the R/V *Akademik Mstislav Keldysh* [8]. We discuss the mechanisms of the origination, time evolution, and wind-driven transport of the SDL waters, as well as the possible effect of the SDL on the Kara Sea's hydrology.

TECHNIQUES AND MEANS OF THE OBSERVATIONS

Use was made of a wide variety of instruments capable of the following: (a) continuous underway recording of the hydrophysical features of the surface layer (a CTD probe of the SBE-911 type built into a flow-through system), (b) vertical profiling of the hydrophysical and bio-optical characteristics at different stations (a CTD probe of the SBE-19 plus type with optional sensors for the transparency and fluorescence), (c) high-rate vertical profiling using a towed CTD probe (Idronaut) in the "on line" mode, and (d) vertical profiling of the current velocity using a towed ADCP probe (Workhorse) at 600 kHz. We used satellite data in the visible and IR spectral ranges for operational applications too.

A brief description of the procedures for using the above instrumentation (except for the flow-through system) during the cruise is given in [4]. Building the hydrophysical probe into the flow-through system allowed us for the first time to perform continuous recording of the temperature, salinity, and density of the surface layer over the whole route of the vessel in the southwestern Kara Sea. The probe was placed into a container with a volume of 100 l fastened on the deck in the middle of the vessel. The seawater was pumped into container with an electric pump through a hose with its inlet at a depth of 0.2–1 m. The perturbations of the aquatic environment induced by the vessel were rather insignificant thanks to the positioning of the hose's inlet outside the wake. The capacity of the pump secured the complete changing of the water in the container within five minutes, which suffices to have a spatial resolution of about 0.5–1.0 miles at the vessel's speed of 5–10 knots. The probe's data were fed into a computer for storage, processing, and on-the-fly displaying with a monitor and printer. This information allowed us to monitor in real time the upper layer's hydrology and to localize the surface fronts, as well as to reveal the configuration and thermohaline features of the desalinated water areas in the southwestern Kara Sea. The CTD profiling at the stations provided estimates of the vertical drops and gradients of the temperature, salinity, and density and allowed us to gain knowledge of the transformation of the hydrological structure in the section from the Ob River's mouth to the St. Anna Trench. We did not use the towed ADCP data in the present paper, because the current velocity estimates from these data were reliable only in water thicknesses deeper than 10 m, i.e., beneath the SDL.

To evaluate some of the SDL's features and its wind-driven transformation and water travel, we used the data sets of the National Centers for Environmental Prediction (NCEP) concerning the near-water wind at a height of 10 m in a grid $1° \times 1°$ in latitude and longitude above the Kara Sea from July to October of 2007. Among others, we used these sets to compute the wind friction stress at the sea surface.

RESULTS OF THE OBSERVATIONS

Figure 1 displays the salinity distribution in the upper layer of the southwestern Kara Sea. In the south, the salinity measures 30–33 psu; then, it decreases northwards and reaches its minimum of less than 16 psu near the margin of the Novaya Zemlya Islands at 75°30′N. From here, the salinity grows in the northwestern direction and exceeds 33 psu in the vicinity of the northern tip of the Novaya Zemlya archipelago. The lowest salinity of a few per mille occurs at the Ob's mouth, but more saline waters separate this low salinity domain from the water of similar salinity close to the Novaya Zemlya Islands. Therefore, the latter represents a quasi-isolated lens.

Figure 2 shows typical profiles of the temperature, salinity, and density of the water at station 1464 in the area of the desalinated waters. This station lies in the Novozemel'skaya Trench and features a low salinity layer (16–17 psu) whose thickness is about 12 m. A narrow pycnohalocline with a salinity jump from 12 to 32 psu occurred at a depth of 12–15 m beneath the low salinity surface layer. A thermocline with a temperature drop from 5 to −1°C occurred at the same depths. At that, the salinity contributes 98% of the density difference, which makes up about 13 arbitrary units. Below the gradient layer, the water's properties vary only slightly with the depth. The salinity continues to increase and reaches a value of 34 psu at the 40–50 m depth, where the temperature reaches its minimum: −1.7…−1.8°C. The latter is caused by the winter under-ice convection. The temperature values of the salinity minimum are close to the freezing point at the given salinity.

The thickness of the SDL only slightly changed from station to station and ranged from 8 to 12 m. The quasi-homogenous layer was missing at the periphery of the desalinated area due to the outcropping of the pycnohalocline. This is evident in Fig. 2b, which depicts the profiles of the hydrological characteristics at station 4990 occupied near the southern tip of the St. Anna Trench. The SDL becomes observable immediately above the Trench of desalinated waters (station 4984, Fig. 2c). Here and at the adjacent stations, the surface salinity exceeds 34 psu with very weak vertical stability of the water column.

Figure 1 demonstrates the configuration of the desalinated water area. Its southern and northern boundaries were at 72°N and 76°N, respectively. The eastward extension of this area remained unclear. If one assumes that the SDL water detached from the river mouths occupied the space between the Novaya Zemlya Islands and the Yamal peninsula, then its area is close to 40000 km^2. Its volume made up 400 km^3 if the average SDL thickness measured 10 m. Assuming that the average salinity of the desalinated waters was equal to 20 psu while the marine water's salinity measured 34.8 psu, the volume of the fresh water made up 170 km^3. This means that the SDL in the southwestern Kara Sea contained about 14% of the total annual runoff of the Ob and Yenisei rivers or 50% of the volume of the June freshet of the same rivers.

The combined examination of the data obtained in the Ob section with the help of the CTD probes as part of the flow-through system and as a towed sensor for

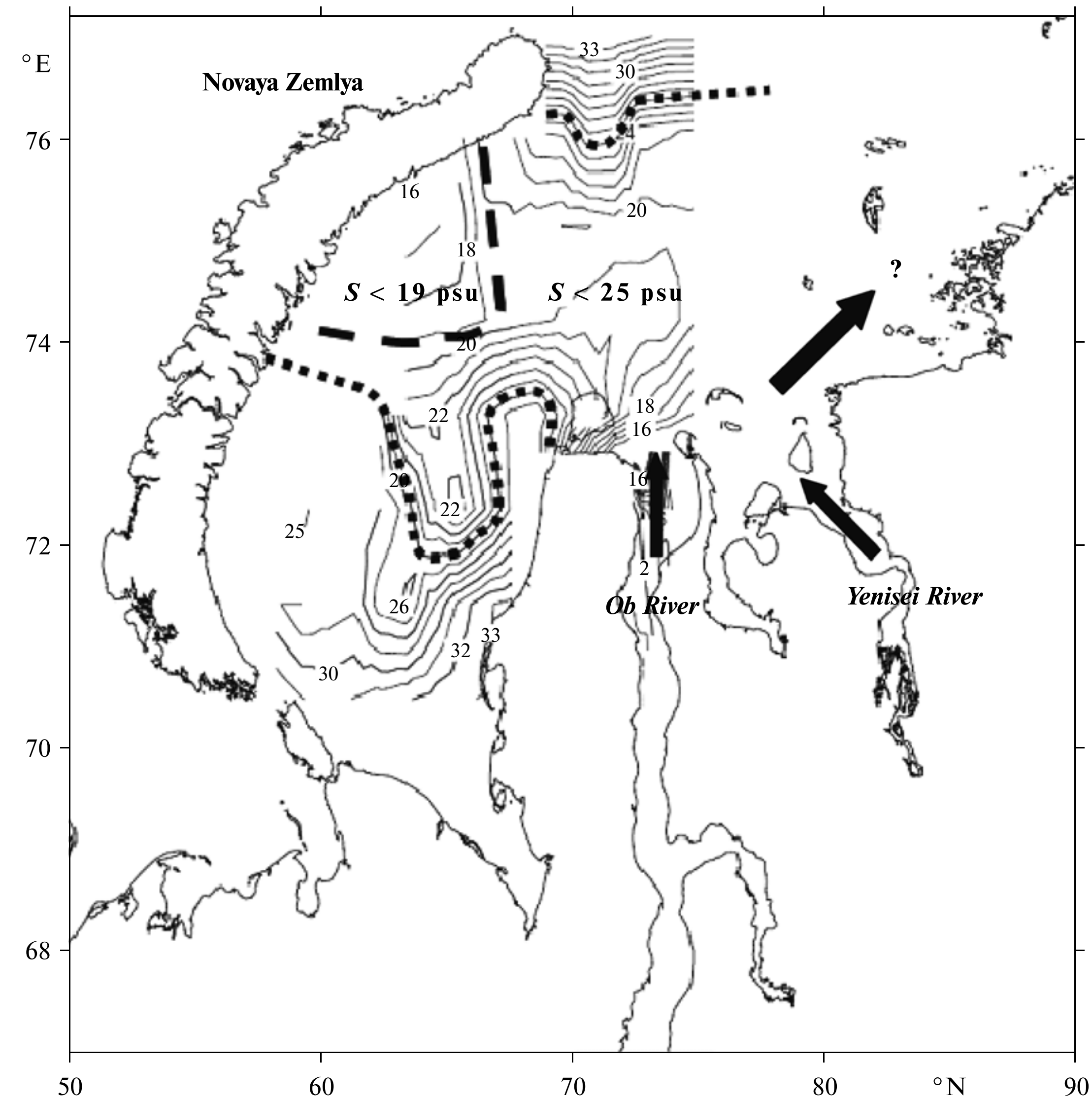

Fig. 1. Distribution of the salinity in the surface layer of the southwestern Kara Sea based on evidence derived from data of the CTD probe built into the flow-through system.

the underway profiling allow us to restore the pattern of the transition from the genuine river water in the Ob mouth to the SDL waters between 73° and 76°N and, next, to the purely marine water to the north (Fig. 3). This figure depicts the latitude dependences of the sea surface salinity from the data of the flow-through system, the near-bottom salinity from the data of the underway vertical profiling of the water thickness, and the depth of the sea according to the vessel's echo-sounder. The quite evident step-wise changes in the sea surface salinity point to the frontal nature of its distribution. The first frontal zone was close to the estuary's sill and delimited the riverine waters and the waters of the SDL. The second one occurred near the St. Anna Trench and delimited the waters of the SDL and the marine waters. In the river estuary, before the sill that peaks between 72° and 72°20′N, the salinity estimates of the waters in the near-bottom and surface layers were no more than several per mille high and similar in magnitude. Above the sill and at its sea side, the near bottom salinity sharply increased up to 30 psu and more. Similarly, the surface salinity increased to about 20 psu, corresponding to the SDL waters.

It is natural to suppose that the mixing of the marine and riverine waters occurs above the sill and at its sea side and that exactly this process results in the formation of the SDL. However, Fig. 3 provides evidence that such mixing occurs in a more intricate manner and need not to be located above the sill. This is corroborated by the riverine water meander discovered within the estuary area far north of the sill (the arrow in Fig. 3 points to the meander). The occurrence of the meander is apparently due to the fact that the current is not purely two-dimensional in nature.

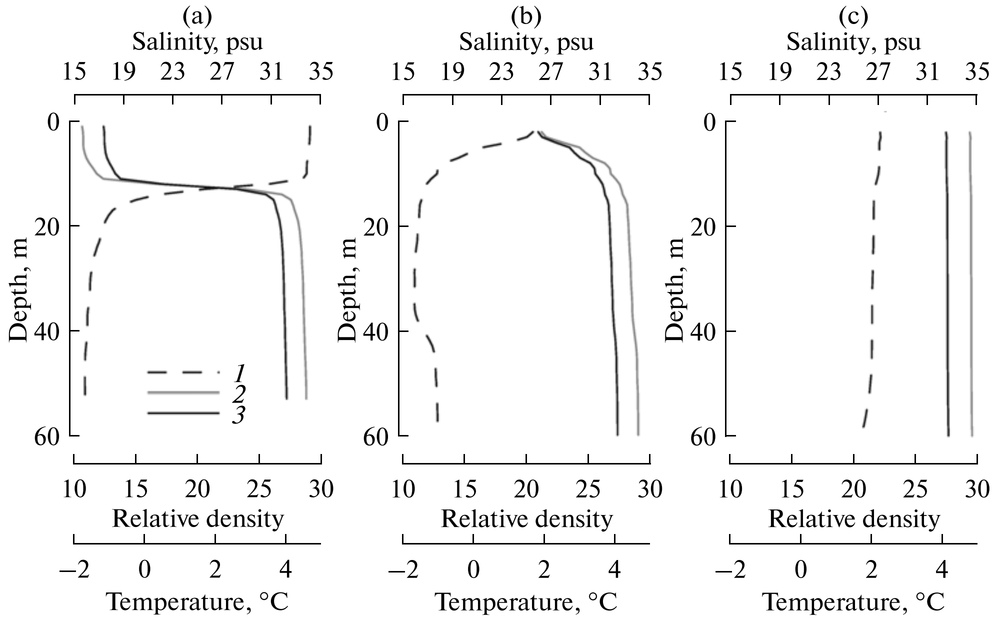

Fig. 2. The vertical profiles of the temperature (*1*), the salinity (*2*), and the relative density of the water (*3*) in the area of the lens of desalinated waters near the Novaya Zemlya Islands at station 4964 (a), in the frontal zone close to the St. Anna Trench at station 4990 (b), and at the St. Anna Trench at station 4984 (c).

Consequently, the different water masses are able to survive for some time at the estuary shore without mixing with each other and with the underlying marine waters. The front that divides the riverine and desalinated marine waters is associated with the sill zone, which is due mainly to the bottom topography and the sharp widening of the aquatic area just beyond the sill in the estuary zone. Notice that the second frontal zone, which divides the SDL and the marine waters of 34 psu salinity, features an association too but in dynamics rather than in topography: the second zone coincides with the frontal zone of the East Novozemelskoe current detached from the shore [4]. Hence, the SDL water having a salinity of 15–25 psu extends from the foot of the Ob's sill at its sea side as far as the St. Anna Trench, i.e., from 73° to 76°N.

DISCUSSION AND ANALYSIS OF THE RESULTS

The comparison of the expansion area of the SDL and its salinity in the Kara Sea with the climatic norm [18] shows that our results depart from the usual patterns: in September 2007, the desalinated waters penetrated westwards further than usual and the salinity of the surface layer water near the eastern margin of the Novaya Zemlya Islands close to 75°–76°N was lower than the norm by about 10 psu. However, in September 1997 and 1999, the desalination of the waters near the eastern margin of the Novaya Zemlya archipelago and north of the estuaries of the Ob and Yenisei rivers was even greater than in the same month of 2007 [9]. Seemingly, one more case of enhanced desalination of the surface layer of the western Kara Sea occurred in the vicinity of the eastern margin of the Novaya Zemlya Islands in September of 1993 when the core of a lens of desalinated waters there featured a salinity magnitude <10 psu [1] unambiguously exceeding the case of 2007 in the salinity deficit. These facts allow us to infer that the degree of the desalination of the sea by the river runoff and other properties of the SDL in the Kara Sea in September 2007 were not exclusive.

Obviously, only the runoffs of the rivers Ob and Yenisei are able to be a source of such a huge volume of water needed for the origination of the SDL and, specifically, of a quasi-isolated lens of the most desalinated waters near the Novaya Zemlya Islands. At first glance, the waters of the river Ob are the main contributor to this lens because the Ob's mouth is closer to the latter as compared with the Yenisei River's mouth. However, the results of the chemical analysis of the SDL waters obtained during the cruise and published in [5] testify in favor of the Yenisei River as the main contributor. In the Ob section, the fresh water balance involves waters of both the Ob and Yenisei. The share of the latter rapidly grows, and the fraction of the Yenisei water is twice as high as that of the Ob water starting from 74°N and up to 76°N. Within the limits of the experimental error, this ratio of the contents of the Yenisei and Ob river waters persists when passing westwards up to the shores of the Novaya Zemlya Islands.

We propose the following scenario of the origination of the SDL in the southwestern Kara Sea. The formation of this layer occurs during the summer freshening of the Ob and Yenisei rivers in three stages.

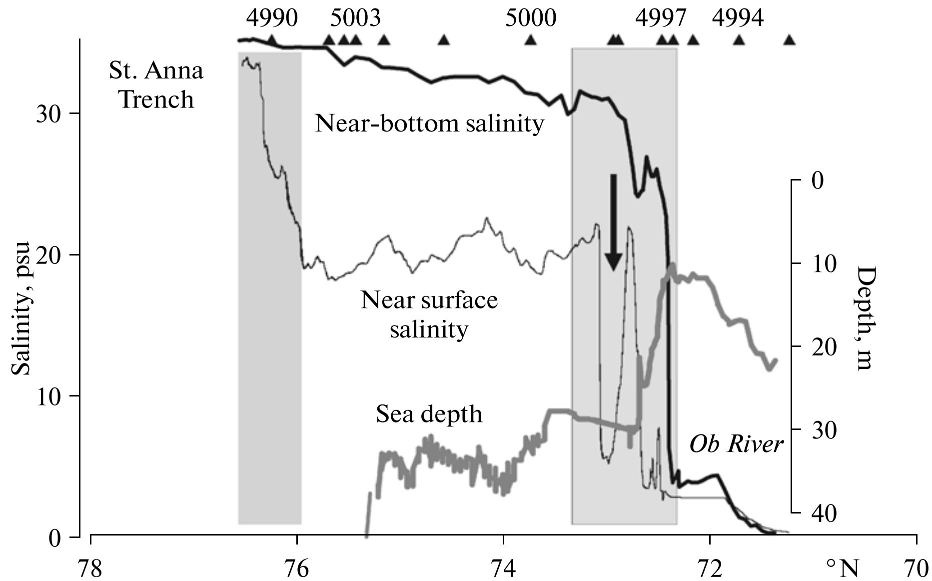

Fig. 3. The salinity near the bottom and in the sea surface layer in the Ob section (cruise 54 of the R/V *Akademik Mstislav Keldysh*). On the top are the station numbers. The grey color marks the frontal zones. The arrow points to the meander of the strongly desalinated waters.

The first stage involves the appearing of river plumes slightly salinated due to the mixing of the marine and riverine waters above the estuary sill and at its sea side. Since the water mixing intensity depends on many factors, including the river water discharge rate, the bottom topography, the phase of the tide, and the wind direction and strength, it is difficult to expect the formation of a desalinated layer well mixed in the vertical and the horizontal during the first stage. It is all the more difficult to expect that the features of this layer (the characteristic salinity, the thickness, the area of expansion, and the configuration) will be similar at the Ob and Yenisei sea sides. June is the main freshening month of the Yenisei river. The discharge rate of the latter in June is more than twice as large as that of the Ob River (Fig. 4). Therefore, it is natural to expect that the Yenisei plume will exceed the Ob one both in volume, in expansion area, and in the salinity deficit. Apparently, this is the cause of the twofold domination of the Yenisei waters in the SDL north of 74°N and in the quasi-isolated lens of desalinated waters near the eastern shore of the Novaya Zemlya archipelago.

The second stage of the SDL formation involves the horizontal water exchange between the plumes of both rivers and their gradual transformation into a quasi-homogenous water mass. The key role in this process belongs to the mezoscale eddy structures emerging at the margins of the river water and the seaward jets, as well as at the fronts in the area of the emerging SDL owing to the baroclinic instability [11]. The vertical homogenization of the SDL water occurs thanks to the turbulent mixing generated by the jet and eddy currents and the wind effects.

We were lucky to reveal the jet–eddy structure of the river plumes at the Ob–Yenisei seaside almost at the peak of the freshening in late June–early July 2007 thanks to the availability of four successive "cloudless" satellite images from the ocean color scanner MODIS-TERRA. The ice fields of diverse dimensions (1–10 km) are easy to see in the images. The pathways of several fields were retrieved from the images by means of the positioning of the fields in each image. Figure 5 shows that the whole region can be subdivided into areas differing in the pattern of the ice displacement. It is possible to classify the areas in the following way: (a) the area of the dominant jet-like motion of the ice; (b) the area of the chaotic (eddy-like) ice displacements; (c) the area of the ordered large-scale transport of the ice fields.

The jet-like ice motion is explicitly coupled with the off-shore propagation of the freshened waters from the near-estuary regions of the Ob and Yenisei rivers. At least two Ob freshened jets and two Yenisei jets of the same kind are observable. They reach 74°N passing into eddy dipoles. The chaotic (eddy) ice motion dominates between the freshened jets of the Ob and Yenisei, as well as to the north up to the boundary marked by the white solid line in Fig. 5 and to the west of the main Ob freshened jet. This motion spans the SDL formation area and is due to the mezoscale eddy dynamics generated by the baroclinic instability of the current at the accompanying fronts, as follows from laboratory experiments [11].

The ice's motion is ordered and mainly eastbound north of the boundary marked by white line in Fig 5. Most likely, this is due to the wind drift: from June 29, 2007 to July 1, 2007, the wind was eastbound and

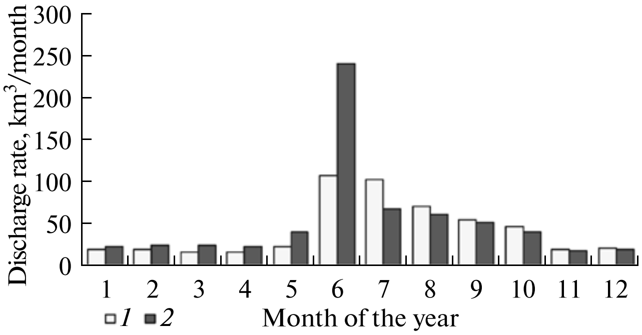

Fig. 4. The annual discharge rate of the Ob (*1*) and Yenisei (*2*) rivers based on evidence from [13].

rather strong (5–10 m/s) over the aquatic area north of the Ob–Yenisei coast. The wind was weak and had little or no effect on the ice displacements at the shore and in the Ob Gulf.

We computed the mean modulus and components of the velocity of the ice transference in each of the above areas based on the relevant data concerning 48 ice fields. The fastest transference occurred in the area of the main Ob jet, where mean modulus $\langle |V| \rangle = 28 \pm 12$ cm/s and the maximum velocity was as high as 60 cm/s. The mean modulus made up $\langle |V| \rangle = 18 \pm 4$ cm/s in the Yenisei jets. This is not surprising, because the monthly mean July discharge rate of the Ob exceeds that of the Yenisei. At that, the Yenisei's discharge sharply drops from June to July, while the discharge of the Ob River remains virtually unchanged: $\langle |V| \rangle = 8 \pm 4$ cm/s in the northern area of the ordered large-scale transfer of the ice fields. In the area of the eddy ice transference, the mean modulus of the current velocity $\langle |V| \rangle = 14 \pm 8$ cm/s, but the modulus of the mean current velocity was close to zero: $|\langle V \rangle| = 3$ cm/s.

Let us insert the dimensionless parameter $C = |\langle V \rangle| / \langle |V| \rangle$, as a measure of the motion's coherence, i.e., the fraction of the directed transfer. In this case, we obtain $C = 0.24$ for the area in question. In the areas of the jet-like motion, $C = 0.96$ for the freshened jets of the Ob River and $C = 0.87$ for the freshened jets of the Yenisei. In the area of the wind drift of the ice fields north of the shore margin of the SDL, we have $C = 0.92$. These estimates quantitatively corroborate the validity of the determination of the transference in the area of the emerging SDL as chaotic or eddy in nature.

According to [3], the coefficient of the horizontal exchange caused by the mezoscale eddy structures is given by the dependence $K = (\langle U^2 \rangle)^{0.5} R_d$, where $((\langle U^2 \rangle)^{0.5}$ is the mean-square velocity of the pulsations in the mezoscale eddy field, and $R_d = (g'H_0)^{0.5}/f$ is the baroclinic deformation radius. In the case of the SDL, $g' = g\beta\Delta S$, where g is the free fall acceleration, β is the coefficient of the salinity contraction, ΔS is the salinity difference between the SDL and the underlying waters, H_0 is the SDL thickness, and f is the Coriolis parameter. Using the following admissions for the area of the chaotic motion, (a) $(\langle U^2 \rangle)^{0.5} = \langle |V| \rangle \approx 14$ cm/s and (b) $R_d = \text{const} \approx 7.5$ km (the calculations are based on the measurement data of ΔS and H_0 during the cruise and on the assumption about the constancy of R_d in the process of the SDL's evolution), we obtain the estimate of the coefficient of the horizontal exchange: $K \approx 10^7 \text{cm}^2/\text{s}$.

The value of the coefficient of the horizontal exchange allows us to estimate the time scale T_d of the eddy interdiffusion of the waters of the Ob and Yenisei origin and their transformation into the unique water mass of the SDL. Omitting the details of this estimation, let us consider the result: $T_d \geq 120$ days. Obviously, such a time scale is comparable with the total duration of the summer floods and is too large for completing the SDL homogenization process within the Ob–Yenisei shore region. This time suffices both for the SDL formation and for its extension over the huge area of the southwestern Kara Sea up to the Novaya Zemlya Islands. This gives grounds to suppose that the horizontal mixing continues over the whole pathway of the propagation of the SDL and that its waters fall short of spatial homogeneity even by the autumn period.

The third stage of the SDL's formation and evolution can occur concurrently with the second one and consists in the advection of desalinated waters to the west. In the absence of wind forcing, the river waters that enter the Kara Sea have to turn to the right in the northern hemisphere and travel alongshore as a surface density current. In this case, the waters of the Ob and Yenisei origin must flow eastwards along the Taymyr peninsula, while the western Kara Sea must be free of desalinated waters. According to [19], this type of propagation of desalinated waters occurs in the Kara Sea in the winter season. However, we observed the situation when more than 50% of the waters of the total June runoff of the rivers Ob and Yenisei traveled westwards and, before the end of August, gave birth to the outlined above surface desalinated layer, including the quasi-isolated lens of the most desalinated waters pressed against the shore of the Novaya Zemlya Islands. The wind drift is the only possible cause of the transference of the desalinated waters to the west and northwest, because there is no evidence of stationary westbound currents in the Kara Sea from the estuary shore of the Yenisei river to the Novaya Zemlya Islands (see paper [4]).

In agreement with the Eckman theory, the total transport of the waters in the sea surface layer occurs at a right angle to the wind direction and to the right of the latter in the northern hemisphere. If one assumes that the desalinated water layer in the Kara Sea complies with the laws of the Eckman boundary layer, then the transfer of the waters in the west and northwest directions has to be driven by northerly and northwest-

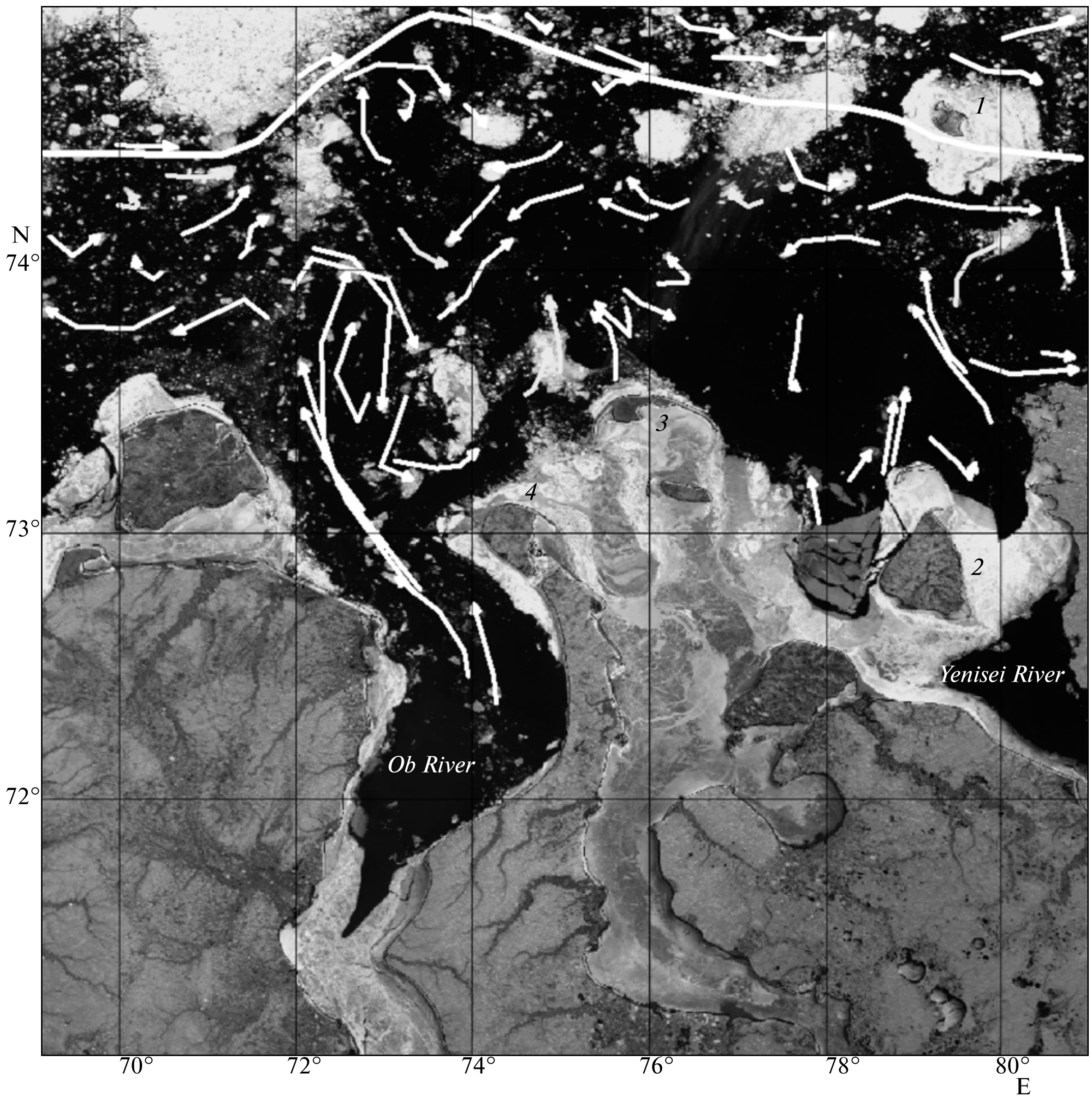

Fig. 5. The ice transference (the arrows show its direction and the arrows' lengths are proportional to its rate) at the Ob–Yenisei estuary and in the surrounding waters based on the data of satellite images of the Kara Sea surface from June 28, 2009 to July 1, 2009 (the MODIS-TERRA ocean color scanner; the visible spectral range). The white bold line depicts the boundary between the chaotic (eddy) and ordered ice motion (above the white line). *1*, Sverdrup Island; *2*, Sibiryakov Island; *3*, Vil'kitskiy Island; *4*, Shokalskiy Island.

erly winds. The analysis of the wind data corroborate this assumption. Figure 6a displays the time-averaged distribution of the wind velocity over the Kara Sea for the period from June to the first half of August 2007 (NCEP data). As follows from this figure, two and a half months are taken to transfer the desalinated waters from the Ob–Yenisei shore to the eastern shores of the Novaya Zemlya Islands while featuring the domination of the northerly wind and, correspondingly, for the integral transfer of the waters of the near-the-surface boundary layer to the west. The southwesterly wind became dominant in the second half of August and September, which must result in the integral transfer of the waters of the near-the-surface layer to the northeastern direction (Fig. 6b). However, this period featured an extremely weak wind of southwestern direction in the southwestern Kara Sea between the Novaya Zemlya Islands and the Yamal peninsula. For these reasons, we failed to reveal the indications of the northwestern transport of the desalinated waters in the data of the observations.

The drift of the SDL in the Kara Sea in response to the Eckman transport mechanism was reported in studies [16, 17] dedicated, among others, to the anal-

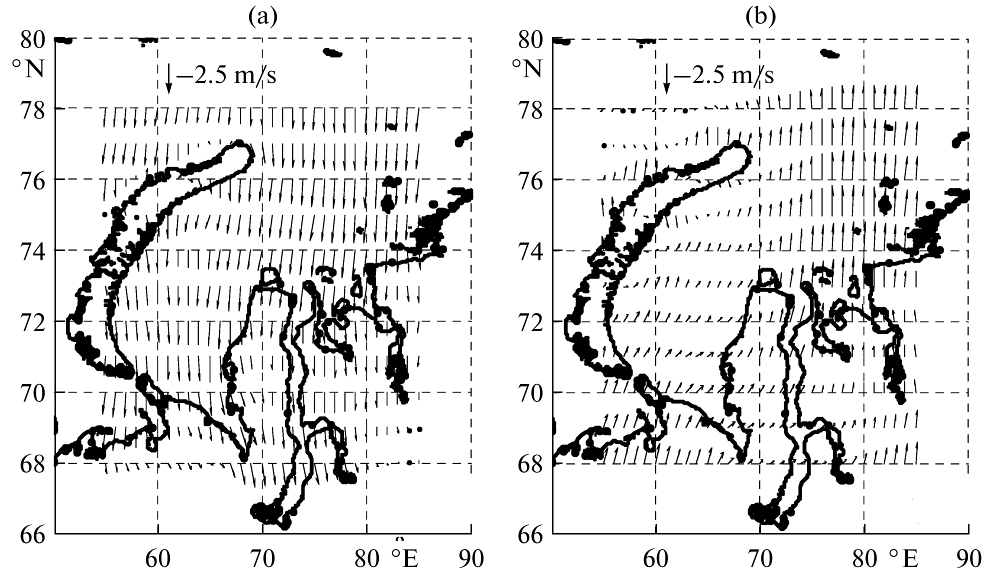

Fig. 6. Distribution of the mean wind velocity over the Kara Sea in 2007 based on evidence from the NCEP. (a) June—the first half of August; (b) the second half of August—September.

ysis of the data on the current measurements in the Kara Sea performed in August—September of 1993—1996 by Norwegian researchers using shipborne ADCP and stationary current meters deployed on anchored buoys. They established the occurrence of a high correlation between the currents in the surface layer 10 m thick and the wind friction stress in the western Kara Sea. At this, the current was always directed to the right of the wind's direction. This correlation was much lower in the eastern Kara Sea, where the SDL was absent in the summer. This fact gives grounds to conclude that the SDL behaves as if it "concentrates" the Eckman transport, which is natural, since virtually all the wind energy obtained by the ocean is transferred to the SDL because of the density jump that suppresses the vertical mixing at the lower boundary of the desalinated layer.

We quantitatively estimated the integral rate of the Eckman transport of the desalinated waters based on the idea of the SDL as a "plate" involved in a common motion [20]. At that, the friction stress generated by the wind at the layer's surface vanishes at the lower boundary of the density jump. The solution of the problem looks like a "classic" expression for the latitudinal components of the rate of the Eckman transport:

$$U_{Ex} = \tau_{y0}/\rho_w f H_0. \tag{1}$$

Here, U_{Ex} is the velocity of the transference of the water within the SDL along the latitude, τ_{y0} is the meridian component of the wind friction stress at the water's surface, ρ_w is the water density, f is the Coriolis parameter, and H_0 is the SDL's thickness.

The velocity of the SDL water transference along the latitude linearly depends on the meridian component of the wind friction stress at the water surface. This allows us to obtain a mean estimate of the $\langle U_{Ex}\rangle$ averaged over a certain time period using the expression for $\langle \tau_{y0}\rangle$ averaged over the same time period.

The computation of τ_0, τ_{x0}, and τ_{y0} (here, τ_0 is the wind friction stress at the water's surface, and τ_{x0} is its zonal component) was performed at five geographical points ((1) 74°N, 70°E; (2) 74°N, 80°E; (3) 75°N, 65°E; (4) 76°N, 70°E; (5) 76°N, 80°E) located in the area of the presence of the desalinated layer from the Yenisei estuary to the eastern shore of the Novaya Zemlya Islands. The computation involved the estimates of the near-water wind velocity averaged over six hour periods. We used the following formula to compute the above characteristics:

$$\tau_0 = \rho_a C_d \boldsymbol{U_a}|\boldsymbol{U_a}|; \quad \tau_{x0} = \rho_a C_d U_{ax}|U_{ax}|; \quad \tau_{y0} = \rho_a C_d U_{ay}|U_{ay}|, \tag{2}$$

where ρ_a is the air density; C_d is the drag coefficient of the sea surface; $\boldsymbol{U_a}$ is the velocity vector of the near-the-water wind at the 10 m height; and U_{ax} and U_{ay} are the components of the near-the-water wind in latitude and longitude, respectively (the east- and northbound winds are positive). To calculate C_d, we used the well-known semi-empirical formula in [10].

The mean values of $\langle \tau_{y0}\rangle$ were found at the above points for the periods from June to mid August and from mid August to late September. The division of the data into two periods is due to the fact that the northern winds dominated during the first of them, while the southern ones prevailed for the second period. The estimates of $\langle \tau_{y0}\rangle$ computed from (1) were used for calculating the rate $\langle U_{Ex}\rangle$ of the latitudinal transport of the SDL waters taking into account that $H_0 = 10^3$ cm. It turned out that the magnitudes of the parameters only slightly changed from point to point for the first period with the point ensemble average $\langle U_{Ex} \rangle = 2.16 \pm 0.69$ cm/s.

Based on the obtained rates of the integral Eckman transport, let us evaluate the characteristic distance that can be traveled by the water of the desalinated layer westwards in two and a half months of drift (T = 75 days) from June to mid-August. This distance makes up $L = \langle U_{Ex} \rangle T = 140 \pm 45$ km. However, the distance between the Yenisei estuary and the eastern margin of the Novaya Zemlya Islands measures about 600 km. Consequently, the integral transport of the desalinated waters must occur approximately four times faster than our estimate predicts.

This is the possible causes of the underestimation of the Eckman transport rate:

(a) The neglect of the presence of masses of ice cakes and solid ice at the sea surface in June–July. The summer observations in the East Greenland Sea [12] provided evidence of a twofold increase in the drag coefficient of the sea's surface Q if ice cakes occupy at least 40% of the aquatic area and a fourfold increase in Q if the area exceeds 70%.

(b) The condition of the constancy of the SDL's thickness $H_0 = 10$ m (in June–August, the SDL could have been thinner, which, according to (1), accelerates the Eckman transport).

(c) The underestimation of the quantities τ_0 when computing them from the data of the wind velocity averaged over the six-hour period (the smoothing of the wind fluctuations of shorter time scales, which are able to yield a heavier contribution to τ_0). Notice that the correction for all of the three factors of the underestimation of $\langle U_{Ex} \rangle$ enhances the wind friction stress and the rate of the integral Eckman transport, which is linearly dependent on the stress, to a degree that appears quite sufficient for supporting the "westward" propagation of the desalinated water layer in the Kara Sea up to the Novaya Zemlya Islands during the summer season.

The wind forcing's influence on the SDL water transport coexists with the substantial effects of the proper dynamics of the desalinated area. In fact, this area represents a huge surface lens of water whose density is lower relative to the surrounding waters. According to the laws of the hydrodynamics of a rotating fluid, the lens must be embraced by anticyclonic circulation [11] with the maximum current velocity near the frontal boundaries of the lens. Our estimates give 10 cm/s and more as probable values for this velocity. The proper anticyclonic circulation of the waters in the desalinated area must facilitate the westward transport of the SDL waters in the region between the Ob–Yenisei shore and the Novaya Zemlya Islands. However, this factor can be important only if the initial westward propagation of the SDL waters takes place thanks to the wind drift.

Let us discuss the issue of the time dependence (evolution) of the vertical structure of the desalinated water layer. It is quite probable that, initially, this layer features very low salinity (about several per mille) and moderate thickness (about five meters). Next, while traveling westwards owing to the wind forcing, the layer deepens and gains salinity due to the turbulent entrainment of marine water from the underlying thickness. The main changes in the salinity and thickness of the desalinated layer have to occur during storms, since the rate of the turbulent entrainment grows with the dynamic friction velocity. We calculated the rate of the SDL deepening using the patterns of the turbulent entrainment found from the laboratory modeling of this process in a nonrotating fluid [21]. The calculations revealed that a twofold increase in the thickness of the desalinated layer had to occur in less than 20 hours at U_a = 14 m/s. In the event that such regime of the entrainment took place, this layer could not survive the storm of September 9–11, when U_a exceeded 14 m/s. Hence, the entrainment patterns used failed to be efficient in this case.

The constancy of the thickness and salinity of the SDL even in the presence of wind is achievable in the near-estuary sea regions where the advection of the river waters into the SDL supports the uptake of positive buoyancy. The ice melting is able to support the positive buoyancy uptake into the upper layer too. However, such a mechanism of the maintenance of the constancy of the desalinated layer's thickness is impossible far from the river mouths in September when the southwestern Kara Sea is free of ice.

Consider now one more aspect of the ice melting's influence on the SDL's salinity and, primarily, on the origination of the most desalinated waters near the Novaya Zemlya Islands. It is known that the Novozemelskiy ice massif occurs every year in the southwestern Kara Sea. The massif forms during the fall–winter season and vanishes due to melting by early September. In late May–early June, the mean ice thickness of the Novozemelskiy ice massif makes up 1.6–1.8 m [15]. Next, two processes begin: the ice melting and the concurrent drift of the SDL waters from the Ob–Yenisei shore to the west. This lasts at least until mid-August. On the assumption of the permanent replenishment of the SDL with the melt water of the Novozemelskiy ice massif, the additional desalination of this layer can be as high as 2–3 psu. Taking into account that the ice massif is nonuniform in thickness and that convergence zones arise in the sea due to the wind forcing and currents where the melting ice accumulates, one can expect that the additional local desalination makes up 4–5 psu. Hence, the melting of the ice of the Novozemelskiy ice massif is a quite probable source of the salinity deficit needed for the origination of the quasi-isolated lens of the most desalinated waters discovered by the authors near the Novaya Zemlya Islands.

The results of the numerical simulation of the water circulation in the Kara Sea [13, 14] are of primary importance for understanding the seasonal variability of the SDL's configuration and the water exchange of the Kara Sea with other seas through the straits. According to these results, no outflow of desalinated water into the Laptev Sea through the Vil'kitskiy strait occurs under the conditions of the northeastern wind typical of August. This inference is indirect evidence of the absence of the Western Taymyr current in the near-surface layer during the warm season, when the SDL occupies the vast area in the central and southwestern Kara Sea. Under the southwesterly wind typical of October and other months of the cold season, the desalinated waters flow along the shores of the Taymyr peninsula without penetrating the central and southwestern Kara Sea. Instead, the drifting withdrawal of these waters into the Central Arctic basin and the Laptev Sea through the Vil'kitskiy strait occurs. The withdrawal of the SDL waters must be particularly intense after the formation of the rugged floating ice, because its presence results in the manifold enhancement of the transfer of the momentum from the wind to the water [12]. Thanks to this circumstance, the SDL rapidly vanishes in most of the Kara Sea's area in the winter season. Thereupon, the haline under ice convection develops and penetrates to a depth of 40–50 m, which results in the formation of the coolest waters of lesser salinity (as compared to the marine waters) and of a temperature close to the freezing point. The process of the under ice convection utilizes the remains of the desalinated water in the Kara Sea through mixing with the marine waters and creates a barrier that prevents the interaction of the warmer and more saline Barents Sea waters and the modified Atlantic waters (propagating at a depth of more than 50 m) with the atmosphere. The haline convection cannot penetrate so deeply in the case of the absence of desalinated waters flowing off to the east.

To generalize our findings concerning the specific features of the propagation and evolution of the SDL for the warm season of 2007, we infer the following:

1. The SDL forms mainly in June, when the total freshening of the Ob and Yenisei rivers is at its maximum. As this takes place, the area of the interaction of the riverine and marine waters is substantially larger than in September and is offset by about 100–150 km from the river mouths to the sea shelf. Although mixing of the waters desalinated by the runoff of the Ob and Yenisei rivers is facilitated by the intensive horizontal eddy exchange, the SDL has no time to reach the state of homogeneity.

2. The western type of the SDL water expansion dominated during the period described, which was due to the prevailing of northerly winds for two and a half months, i.e., from early June to mid August. The wind forcing supported the drifting transport of the desalinated waters from the Ob and Yenisei estuaries to the eastern margin of the Novaya Zemlya Islands. The estimation of the rate of the westward Eckman transport of the desalinated waters gives values comparable to the observed ones if an allowance is made for the 2- to 4-fold increase in the drag coefficient of the sea surface covered with floating ice of high concentration with respect to the free water surface.

3. The westward extent of the desalinated waters and the level of their desalination in September 2007 exceeded the climatic norm. However, even greater water desalination occurred in September 1997 and 1999 to the north of the Ob and Yenisei estuaries and near the eastern margin of the Novaya Zemlya Islands. The desalination of the surface layer in the western Kara Sea, which was stronger than in 2007, also occurred in September 1993 when the lens of desalinated waters with salinity < 10 psu in its core was observed near the eastern margin of the Novaya Zemlya Islands. Hence, the desalination level of the marine waters and the area belonging to the SDL in the Kara Sea in 2007 were not extreme in magnitude.

4. The June freshening of the Yenisei was more than twice as strong as the Ob freshening. For this reason, the SDL found north of 74°N and, specifically, the desalinated quasi-isolated lens near the eastern margin of the Novaya Zemlya Islands involved much more water from the Yenisei River than from the Ob River [5]. A certain contribution (an extra salinity decrease by 2–5 psu) to the formation of the quasi-isolated lens of desalinated waters could be attributable to the melting of the Novozemelskiy ice massif.

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