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On the Mechanism of Wind-Induced Transformation of a River Runoff Water Lens in the Kara Sea

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Abstract—The paper describes a possible mechanism for the transformation of a desalinated water lens in the Kara Sea under the action of vertical turbulent mixing induced by wind. Using a simple one-dimensional model, we show that the strongest transformation occurs at the edge of the lens—its frontal zone, where the thickness of the desalinated layer is the smallest. Because of the strong (cubic) nonlinear dependence of the turbulent energy flux on the wind speed, significant transformation of the frontal zone of the lens occurs during storm events. A series of consecutive storms can cause horizontal lens fragmentation into several zones in which the salinity increases spasmodically towards the edge of the lens.

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INTRODUCTION

One of the most characteristic features of the hydrologic structure of the Kara Sea is the presence of a surface desalinated layer (SDL) in the summer–winter period, which forms in the southern part of the sea from Ob and Yenisei river runoff and covers a significant part of the sea's water area [4, 5].

Because it has a lower density than seawater, riverine water spreads in the form of a lens in a surface layer with a thickness on the order of 10–15 m. With distance from a river's mouth, the salinity of waters in the upper layer on average increase due to the mixing of river and sea waters. As well, the change in salinity does not occur uniformly and gradually, but has an inhomogeneous "jumplike" character as a result of the nonlinearity and variability of interaction between riverine water, the surrounding sea, and the near-water atmospheric layer [1]. In other words, the desalinated lens contains frontal sections. Some of these are related to vortices that break up the desalinated lens, probably as a result of baroclinic–barotropic instability [2, 8]. Frontal sections can also apparently form at the boundaries of desalinated waters of different origin: from the Ob and Yenisei. However, some of these fronts are induced by wind, which is rather variable and sometimes quite strong.

A condition for the retention of a desalinated lens, at least to an extent of several meters (June–October) is the large fluctuation in density through the freshwater–seawater interface. It reaches about 20 units of conditional density, so the processes by which seawater is entrained in the desalinated river runoff lens occur weakly even under the action of strong winds [2, 3]. However, the condition of weak entrainment is met in the case when the lens has already formed and is of sufficient thickness. At the initial state of its formation, when it is comparatively thin (the first few meters along the vertical), the entrainment processes apparently occur quite quickly. In particular, this is evidenced by the results of [10, 11], which describe the processes of transformation of river waters in the near-coastal zone of the sea based on observations and simulation. They show that the transformation region itself consists of two parts: near and far. In its near part, located close to a river's mouth, mixing of sea and river waters occurs owing to the energy of the shift in the inertial flow velocity generated by river runoff, as well as to wind action. In the far (sea) part, when the inertial flow attenuates, wind action plays the main role in water transformation.

Here, the most vulnerable to mixing are the edges of the lens, when the thickness of the desalinated layer is relatively small. There is evidence that it is the frontal zone of the lens that is subjected to destruction during storm impacts [9]. This paper proposes a simple one-dimensional model that can theoretically substantiate the effect of transformation of the lens' frontal zone under the action of turbulence generated by wind friction tension. After the strong wind action ends, restratification of the edge (frontal) zone of the lens occurs; however, the salinity in the region subjected to mixing increases due to the entrainment of

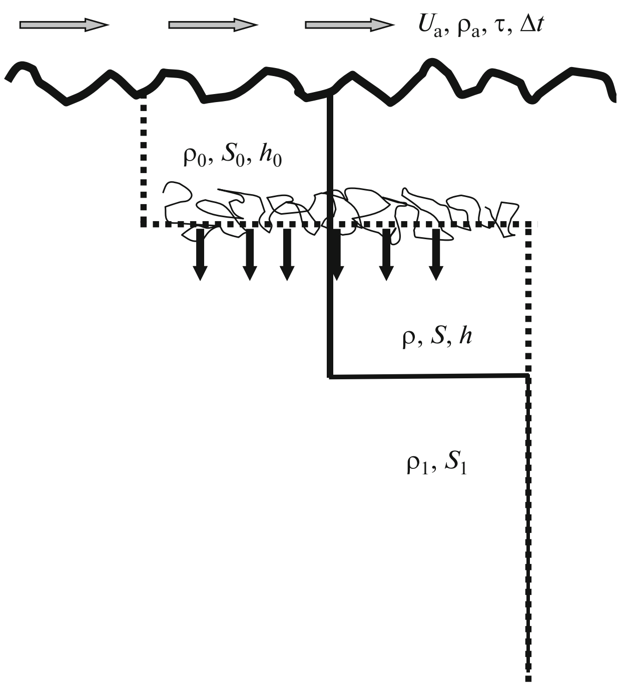

Fig. 1. Diagram of deepening and salinization of upper mixed layer due to turbulent entrainment of more saline water from lower-lying layer during wind action.

seawater, and this zone is separated from the water of the main lens by the newly formed salinity front. In the wind-transformed edge zone of the lens, as a rule, increased biological production is observed, caused by the entrainment of nutrients from deeper water layers in the stratified near-surface layer. This means that this process also influences the biotic component of the Kara Sea ecosystem [6, 7].

Thus, as a result of quasiperiodic action of strong winds, the edge (frontal) zone of the lens can separate into a number of regions, between which water salinity varies appreciably. The paper presents some examples of transformation of the edge zone of the desalinated lens and its possible separation due to wind action, observed on cruise 59 of the R/V *Akademik Mstislav Keldysh* in September 2011.

MODEL OF VERTICAL MIXING OF THE FRONTAL ZONE OF THE DESALINATED LENS

Questions arise: how does the frontal zone of the lens become separated, its waters salinized, and how are they transformed? A similar transformation is impossible without the expenditure of mechanical energy required for mixing less dense, fresh river runoff waters with denser seawater. In the upper sea layer, the main source of mixing energy is wind. Wind action creates turbulence in the upper quasiperiodic layer (UQL) of the sea. A large part of the turbulence energy dissipates due to viscous tension, but a certain fraction of it is consumed by the entrainment of denser water into the UQL from below. If the UQL is desalinated by river runoff, then the more saline underlying water is entrained and mixed with the fresher waters of the upper layer. As well, the upper layer is salinized and its thickness increases.

Figure 1 depicts the penetration and densification of the upper layer due to turbulent entrainment of fluid from the underlying layer.

To quantitatively evaluate the above-mentioned process, we will consider that stratification of fluid is two-layered; the upper layer is characterized by the initial density ρ_0 and thickness h_0; the lower layer, by the density ρ_1, and it is initially much thicker that the upper layer. The water density profile corresponding to the initial state of the two-layered system is shown in the figure by a dotted line. Wind action is depicted in Fig. 1 as a rough sea surface, as well as the indicated parameters of the atmosphere, including the wind speed U_a, air density ρ_a, and wind friction tension τ on the sea surface. After termination of wind action with a certain force and duration, due to turbulent entrainment of the denser water from the lower layer into the upper, the density of the upper layer increases to density ρ and its thickness increases to depth h. The water density profile corresponding to the final state of the two-layered system is shown in Fig. 1 by the thick solid line.

We accept that to increase the potential energy of the upper layer due to its density and penetration, a certain fraction of the energy flow of turbulence coming from the wind is expended, which has at a height of 10 m above sea level, a velocity U_a (let this be constant), and a duration of action Δt. We will also consider that there is no mass (heat, salt) exchange between the upper layer and atmosphere. Then, we have the two initial equations

$$(g'h)dh/dt = 2\gamma U_*^3, \quad (1)$$

$$g_0' h_0 = g'h. \quad (2)$$

Here $U_* = (\tau/\rho_w)^{0.5} = (C_d\rho_a/\rho_w)^{0.5} U_a \approx 1.3 \times 10^{-3} U_a$ is the dynamic velocity of friction in water; τ is the wind friction tension on the sea surface; $C_d \approx 1.3 \times 10^{-3}$ is the coefficient of resistance of the sea surface; $\rho_a \approx 1.3$ kg/m^3 is the air density; $\rho_w = 10^3$ kg/m^3 is the water density; U_a is the wind speed at a height of 10 m above sea level; $\gamma = 0.05$–0.25 is the efficiency coefficient [11]; $g_0' = g\Delta\rho_0/\rho_1$ and $g' = g\Delta\rho/\rho_1$ are the reduced acceleration of free fall (the initial and current values, respectively); and $\Delta\rho_0 = (\rho_1 - \rho_0)$ and $\Delta\rho = (\rho_1 - \rho)$ are the fluctuation in density through the interface between layers (the initial and current values, respectively).

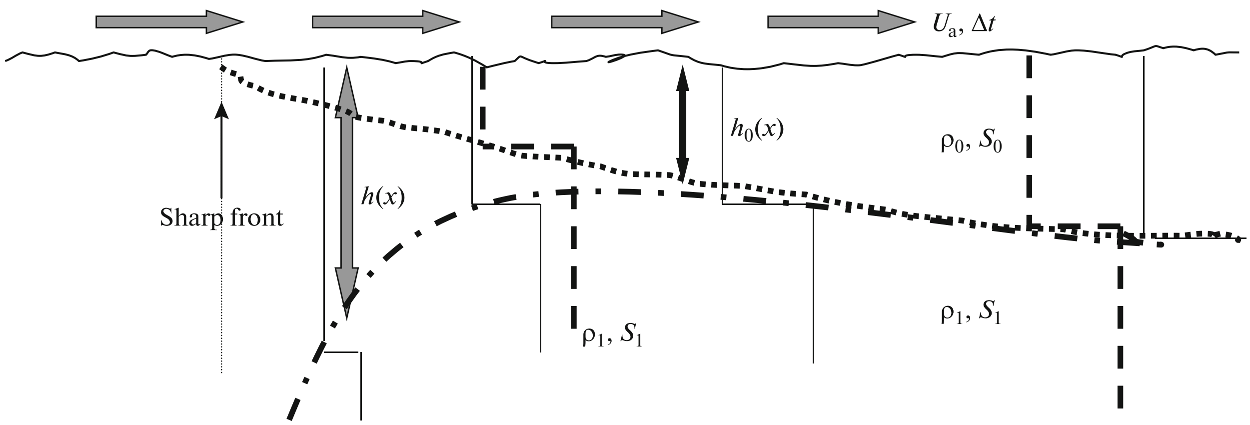

Fig. 2. Diagram of transformation of desalinated water layer column in edge (frontal) part of lens.

The solution to system of equations (1), (2) has the form

$$h = h_0 + 8.8 \times 10^{-9}(\gamma U_a^3 \big/ g_0' h_0)\Delta t. \quad (3)$$

Here Δt is the time interval for integration of system of equations (1) and (2), corresponding to the duration of wind action.

From (3) it follows that an increase in the thickness of the upper layer is proportional to the wind speed cubed. This means that an increase in wind speed by two times leads to an eightfold acceleration in the penetration and salinization rate of the upper layer!

It is easy to bring (3) to dimensionless form and estimate the relative increase in thickness of the upper layer and its relative densification (salinization):

$$\begin{aligned}(h - h_0)/h_0 &= \Delta h/h_0 = (\rho - \rho_0)/\Delta\rho \\ &= 8.8\times 10^{-9}(\gamma U_a^3 \big/ g_0' h_0^2)\Delta t.\end{aligned} \quad (4)$$

From (4) it follows that the relative increase in layer thickness $\Delta h/h_0$ and the increment of its density $(\rho - \rho_0)/\Delta\rho$ quadratically decreases with increasing layer thickness h_0. This means that sufficiently thick water layers (the central part of the desalinated lens) will behave conservatively and weakly change their characteristics even under the action of strong wind, whereas thin layers (the boundary (frontal) part of the lens) thickens and densifies relatively easily under wind action.

Figure 2 schematically shows the transformation of the thickness of the upper desalinated water layer. The initial state of the density interface of the lens with the surrounding seawater is denoted by a fine dash-dot line. The large dashed line shows the water density profiles in different areas of the desalinated lens. The initial state of the lens, just like in Fig. 1, is characterized by the following parameters: density ρ_0, salinity S_0, and desalinated water layer thickness $h_0(x)$, where x is the horizontal coordinate counted from the edge (front) of the lens on the sea surface. The ultimate thickness of the desalinated lens $h(x)$ after wind action and turbulent entrainment is shown by hashmarks. As follows from relation (3), as the initial front of the interface of the desalinated lens is approached, the thickness of the upper desalinated water layer, transformed by wind action and turbulent entrainment, hyperbolically tends to infinity. In fact, this means that the thinnest boundary part of the lens mixes with the surrounding water.

Let us now consider in more detail the transformation of river water entering the sea during and after wind action (Fig. 3). Before the onset of strong wind action, these waters spread above saline seawater in the form of a wedge, the thickness of which gradually decreases in the direction of its spreading right up to zero (Fig. 3a). At this spot, a sharp front on the sea surface is observed, where the water density nearly changes jumpwise from ρ_0 to ρ_1. As already mentioned, during a storm, the thinnest (nose) portion of the wedge is subjected to the greatest penetration and salinization. As a result, the water wedge, transformed by storm mixing, will seem to consist of two parts: the significantly transformed nose portion and the weakly transformed tail portion (Fig. 3b). Because the water salinity in the nose portion is inhomogeneous, this part of the wedge after storm action becomes restratified, spreads horizontally, and turns into the new frontal interface, where the isopycnics come to the surface (Fig. 3c).

Since river water enters the sea quasi-continuously, the untransformed and transformed parts of this water will gradually advance toward the open sea. During a new storm event, the wedge of the transformed part of desalinated water will again split into two parts: the nose, which will transform even more strongly, and the tail, which will be subjected to a smaller transformation. Following the above scenario, the desalinated water of the lens adjacent to the river mouth after several storm impacts will consist of a number of belts divided by frontal sections and the water salinity will increase seaward from belt to belt.

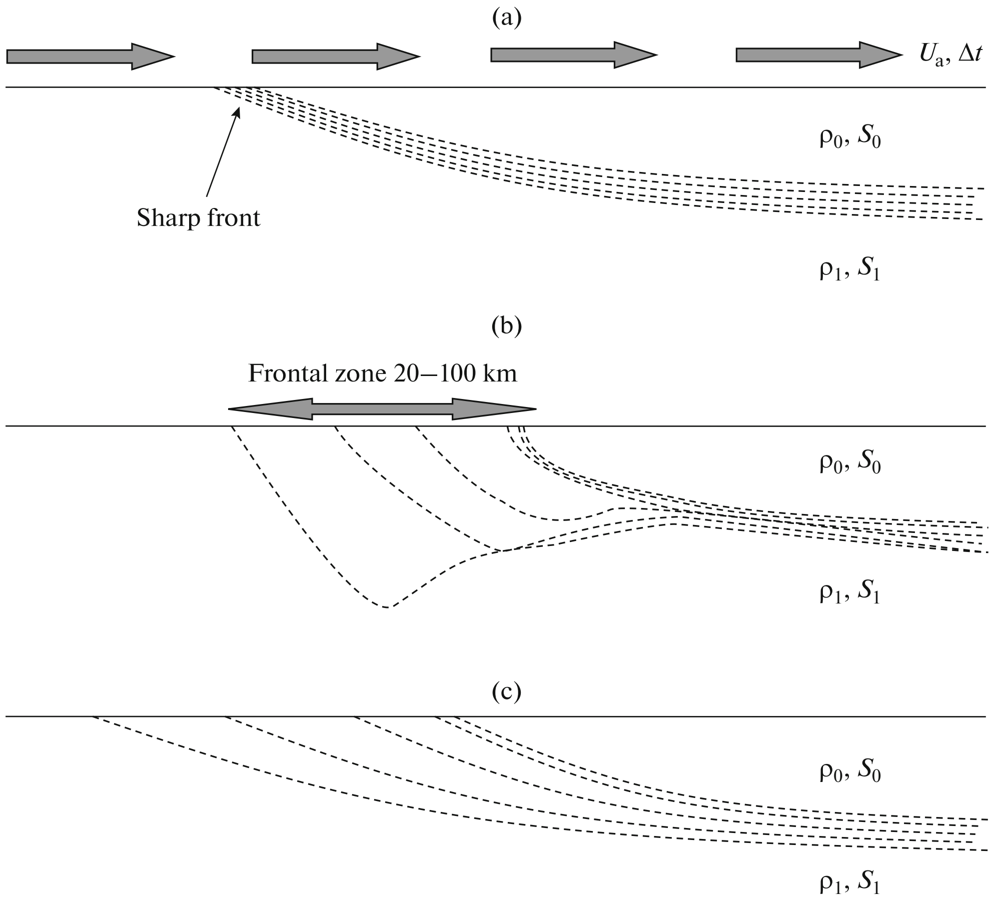

Fig. 3. Diagram of deepening and salinization of frontal edge of desalinated lens as result of wind action (a) position of interface between upper and lower layers before wind action; (b) formation of intermediate water mass between low-transformed waters of the lens and surrounding seawater; (c) formation of new frontal region as result of propagation of transformed water mass.

We should also touch upon the question of how wind direction influences the above-mentioned process of mixing and transformation of water of the edge (frontal) zone of the desalinated lens. From physical considerations it follows that wind action can either facilitate or hinder thinning of the frontal wedge. Therefore, the degree of transformation of water in the frontal zone of the lens should also depend on the direction of wind action.

The next section presents some examples of how the above-mentioned mechanism of wind mixing of waters in the frontal zone of the lens can be realized in the Kara Sea.

TRANSFORMATION OF THE DESALINATED LENS IN YENISEI COASTAL WATERS

Possible manifestation of the influence of wind action on the frontal structure of water of the desalinated lens was recorded on cruise 59 of the R/V *Akademik Mstislav Keldysh* on the Yenisei transect. On this transect, on September 17–18, 2011, the water column was profiled by a Rybka towed scanning sounder (TSS) from north to south from Yenisei coastal waters (station 5010) to the mouth of the river (station 5013). Complex oceanological stations were placed (Fig. 4) on the return route from south to north.

Owing to the large frequency of Rybka TSS soundings, it was possible to represent from its data the fine horizontal and vertical structure of the frontal zones and sections into transition regions from marine moderately saline waters (stations 5010–5011) to virtually fresh river waters (stations 5012–5013). As well, the frontal sections are identified by the inclined thickening of isolines fraying out either to the surface or to the bottom.

Figure 5 shows a large fragment of the Yenisei profile in the salinity field, constructed from the Rybka TSS data. The left edge of this fragment is located approximately at the spot of station 5016 in the mouth of the river, and its right edge approximately corresponds to the position of station 5021 at the northern end of Yenisei Bay on the Taimyr traverse (see Fig. 4). The total length of this area of the transect in 130 km. Two main frontal sections in the surface layer separate waters of differing salinity (Fig. 5). The front at a dis-

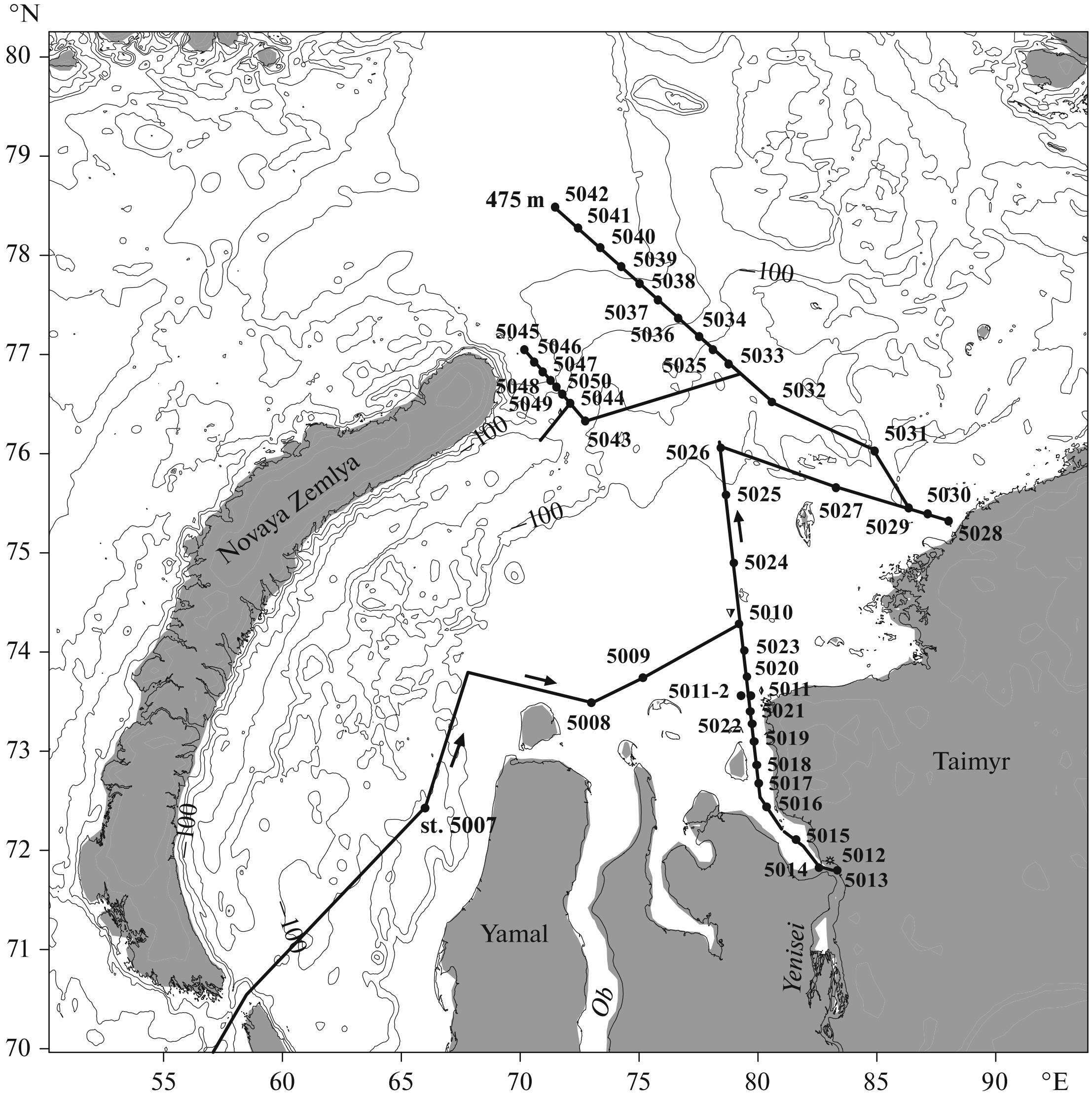

Fig. 4. Map diagram of vessel transects with stations set up on cruise 59 of R/V *Akademik Mstislav Keldysh*.

tance of 30–35 km from the left edge of the figure, at approximately 72°40′ N between stations 5016 and 5017, separates the virtually fresh (0–10 psu) water from the strongly desalinated water (10–20) psu, extending up to 75 km along the profile. The front at a distance of 110–120 km along the profile at approximately 73°25′ N in the vicinity of station 5021 separates the strongly desalinated water from the moderately desalinated saline water (20–30 psu), which occupies the majority of the Kara Sea water area and represents the SDL [2, 3]. It should be noted that between the isolated fronts, there is a meander zone of more saline waters, which "cuts" the continuous structure of Yenisei waters spreading to the north along the Taimyr coast.

It is our assumption that in the period of freshwater propagation along Yenisei Bay to the coastal waters, the waters, as a minimum, are subjected once to strong wind action. Figure 6 shows the dependence of function U_a^3 (the near-coastal wind velocity squared) on time (from May 1 to October 1, 2011). The plots are constructed from the NCEP one-degree reanalysis data for two points in the area of the Yenisei transect: one at 72° N (beginning of the transect, Fig. 6a), and the other, at 73° N (middle of the transect, Fig. 6b). For convenient interpretation, these plots are smoothed with a 10 day-window. From this it follows that the events of strong ($U_a^3 \geq 400$ m^3/s^3) and prolonged wind are observed approximately once every two to four weeks; in phase, these events practically coincide with each other for both chosen points. However, the force of the wind was substantially larger at 73° N, where the screening effect of the coasts is smaller.

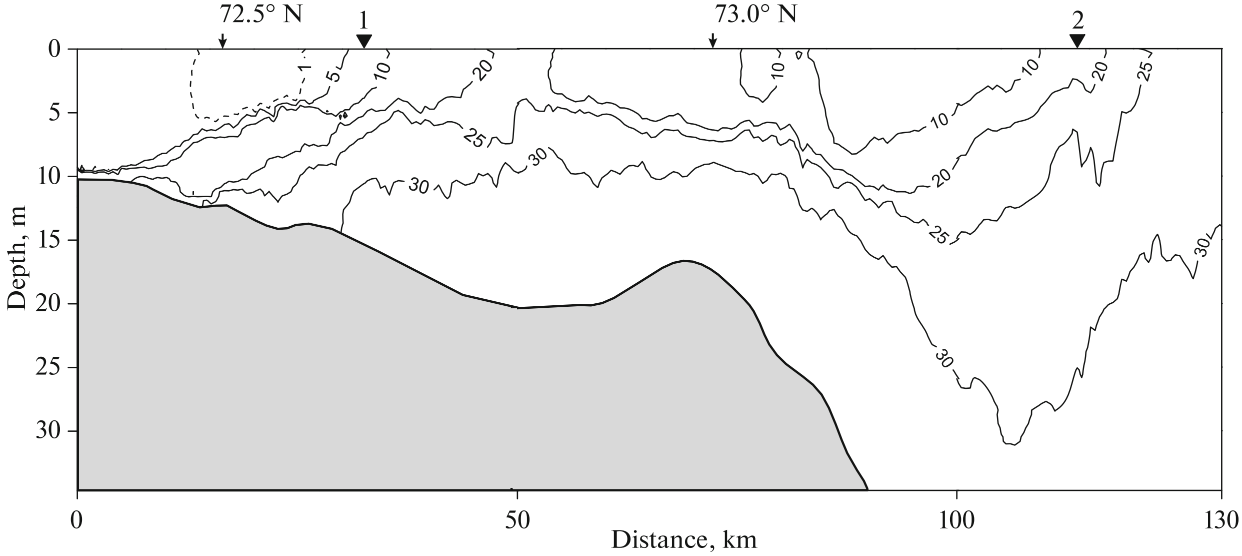

Fig. 5. Distribution of water salinity (psu) in chosen area of Yenisei transect according to Rybka TTS data.

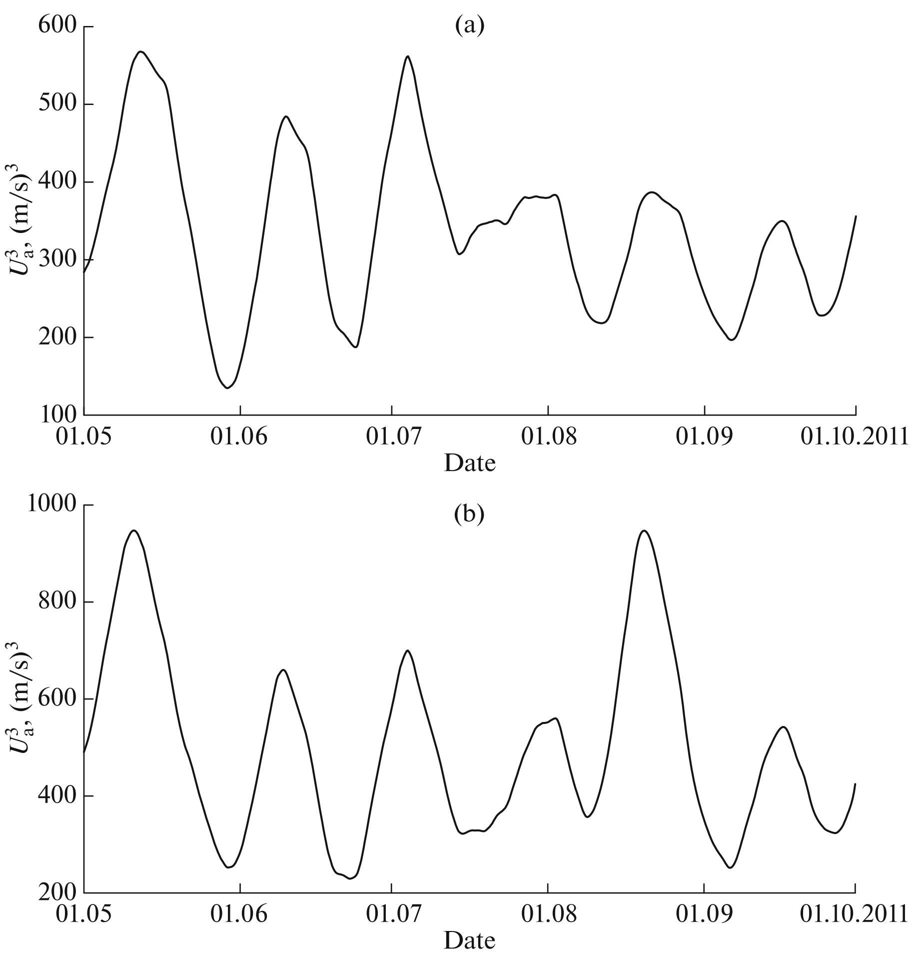

Fig. 6. Time of near-surface wind velocity (U_a^3, (m/s)^3) averaged with 10-day window for period from May 1 through October 1, 2011, at points (a) 72° N, 80° E (start of Yenisei transect) and (b) 73° N, 80° E (middle of Yenisei transect).

It can be expected that the frontal zone of desalinated waters from the Yenisei are transformed with the above-mentioned periodicity. It should be noted that the last wind action in the chosen time period occurred only within several days of the Yenisei transect, and the previous and strongest, in the last ten days of August (Fig. 6).

Let us assume that precisely these winds led to transformation of the frontal zone of desalinated waters coming from the mouth of the Yenisei. Let us estimate the width of the zone of strong water transformation for the last wind action, using formula (4). Here, we will consider that the boundary of this zone is determined by the value $\Delta h/h_0 = 1$, which corresponds to the condition of doubling of the initial width of desalinated waters as a result of wind action. Using (4), we calculate the value h_0 for which this condition is met. For calculations we use the following quantities of the determining parameters: $\gamma = 0.2$; $U_a^3 = 400\ \mathrm{m^3/s^3}$; $g_0' = 0.12\ \mathrm{m/s^2}$, $\Delta t = 5.2 \times 10^5$ s (~6 days), which approximately correspond to the conditions of strong wind action in September. Substituting these values into (4), we obtain $h_0 = 1.8$ m. Considering that the tangent of the angle of inclination of the front of the desalinated wedge to the horizontal is $\tan\alpha = 2.5 \times 10^{-4}$ deg, we obtain $L_{tr} = h_0/\tan\alpha = 7.2$ km. This value approximately corresponds to the distance at which the salinity of the wedge of Yenisei waters varies from 0–1 psu to 10 psu 30–40 km from the start of the transect. Accordingly, a transformed water mass with a salinity on the order of 10 psu, located on the transect between 85 and 110 km, was able to form mainly as a result of two strong wind events—in August and September (see Fig. 6).

The characteristic distance between the main surface frontal sections on the Yenisei transect is 80 km. If we consider that the velocity of desalinated water propagation to the north along the Taimyr coast does not exceed 3–4 cm/s (estimated from several sequential satellite images), then the time it takes for these waters to move to the mentioned distance will be from 20 to 27 days. Such a time scale corresponds to the periodicity of strong wind events characteristic for this area (see Fig. 6). Thus, strong wind events occurring with an interval of several weeks could very likely have resulted in the observed transformation of freshwater runoff en route from the mouth of the Yenisei to coastal waters.

In the course of future expeditionary studies, it seems expedient to conduct special research into the influence of wind action on water transformation, as well as on the processes of frontolysis and frontogenesis in edge regions of the lens. For a detailed study of the patterns of water transformation of a desalinated lens, it seems expedient to use numerical and laboratory lens dynamics models that take into account the Earth's rotation, wind action, and turbulent mixing and entrainment.

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