ISSN 0001-4370, Oceanology, 2015, Vol. 55, No. 6, pp. 827–831. © Pleiades Publishing, Inc., 2015.
Original Russian Text © N.V. Zhurbas, P.O. Zavialov, 2015, published in Okeanologiya, 2015, Vol. 55, No. 6, pp. 916–921.

MARINE PHYSICS

Effect of Stratification on Wind Drift of River Runoff in the Kara Sea

N. V. Zhurbas[a, b] and P. O. Zavialov[a]

[a] *Shirshov Institute of Oceanology, Russian Academy of Sciences, Moscow, Russia*
[b] *Moscow Institute of Physics and Technology, Dolgoprudnyi, Russia*
e-mail: nvzhurbas@gmail.com

Received June 17, 2015; in final form, June 25, 2015

Abstract—The formation mechanism of the Yenisei and Ob Rivers floodwater lens (detected in the Kara Sea near the eastern coast of Novaya Zemlya in September to October 2007) by wind drift is examined. Numerical calculations of the trajectories of Lagrangian floats launched at the north part of the Yenisei and Ob seaside and transported by drift currents have been performed using actual wind-forcing data. Four different algorithms have been used for calculating the surface drift velocity and the relative wind direction; two account for the effect of density stratification due to the presence of a layer of fresh water on the sea surface. It has been shown that only wind-drift models that take into account the presence of stratification are able to explain the transport of the Yenisei and Ob floodwater to the point of lens detection.

DOI: 10.1134/S0001437015060223

1. INTRODUCTION

According to the classical Ekman theory [5, 6], Coriolis forces direct the wind-driven current on the sea surface at an angle of 45 degrees to the right (left) of the wind direction in the Northern (Southern) Hemisphere. In this idealized model, the absolute velocity and direction were calculated on the assumption of stationary movement, the constant coefficient of vertical turbulent exchange and the Coriolis parameter, and a homogeneous ocean of infinite depth. However, in an actual purely turbulent flow near the sea surface, the coefficient of eddy viscosity can vary with depth [4]. This fact was taken into consideration for the simulation of wind drift by Madsen [9], who obtained an analytical solution for the problem of Ekman drift for linear increase in the coefficient of turbulent exchange with depth (wave effects were not considered). Madsen showed that, in this case, the deviation angle of the drift direction is significantly lower than that calculated by Ekman; for realistic values of model coefficients, it is about 10° [9], as confirmed by experimental data [11, 12].

The above models of wind-driven currents considered a nonstratified homogeneous liquid, which is a significant idealization. The consideration of stratification makes it possible to simulate a wide range of phenomena, e.g., the transport of river runoff to the sea, where a freshwater lens forms above the denser seawater. Price and Sundermeyer [10] proposed a simplified model of stationary wind drift in a two-layer stratification at a constant eddy viscosity coefficient within each layer, and model calculations showed that stratification affects transport. The nonstationary problem of the effect of the freshwater layer on wind drift was considered in [1]; it was shown that the water layer of a lower density at the ocean surface increases the absolute velocity of the drift current and its angle with respect to the wind direction, compared to its undisturbed state in the absence of a freshwater layer at the surface.

The quasi-isolated freshwater lens detected in September to October 2007 at the eastern coast of Novaya Zemlya in the Kara Sea, at about 400 and 600 km to the west-northwest from the mouths of the Ob and Yenisei, respectively (between 74° and 76° N), was described in detail by Zatsepin et al. [2]. The area and thickness of the lens were estimated as 4×10^4 km^2 and 10 m, respectively, at characteristic salinity values of 16 to 17 PSU at the sea surface (Fig. 1). From the analysis of the hydrometeorological situation, it was concluded that the formation of the freshwater lens is related to the June flood (a large discharge of river water to the sea) followed by the Ekman transport of freshwater to the west under the impact of the prevailing northern wind in June to August.

Zatsepin et al. [2] quantified the integrated velocity of the Ekman freshwater transport from the concept of the surface freshwater layer as a plate of thickness h moving with a depth-constant velocity. To cover the distance from the mouths of the Yenisei and Ob to the lens position at the eastern coast of the Novaya Zemlya in 75 days (from early June to mid-August), the mean velocity of freshwater transport should be 0.06–0.09 m/s. Zatsepin et al. [2] obtained velocity values below the expected ones. They continued the studies of the distribution mechanisms of freshwater from the Ob–Yenisei coast over the Kara Sea [3] using an approach based on the joint consideration of wind drift and geostrophic currents. This method was successfully verified by comparison with natural observa-

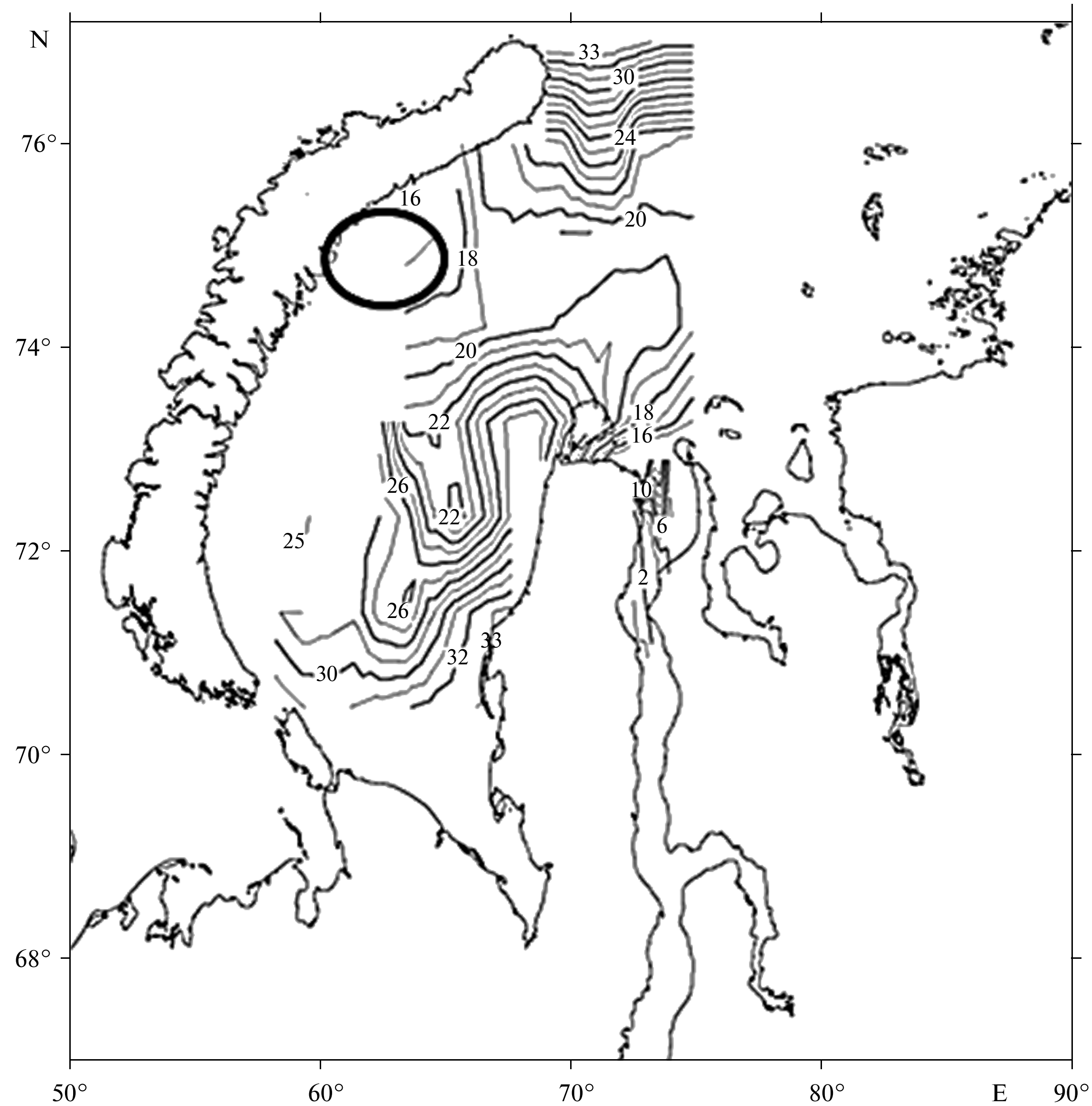

Fig. 1. Salinity distribution in the surface layer of the southwestern Kara Sea from the data of the CTD probe in a flow-through system and the position of a freshwater lens at the eastern coast of Novaya Zemlya in early fall of 2007 [2].

tions in the Kara Sea and satellite images of sea surface chlorophyll; it follows that geostrophic currents formed in the frontal zone between the fresh and sea water also play a significant role in the transport of water from the surface fresh layer. The authors [3] accounted for the impact of wind on the basis of the classical Ekman model [5, 6].

The aim of the current work was to explain the position of the freshwater lens detected in the Kara Sea near the eastern coast of the Novaya Zemlya in September to October 2007 using numerical calculations with different models of wind drift and the approaches outlined below most adequately describing the impact of wind on the sea surface layer.

2. USE OF WIND-DRIFT MODELS FOR THE CALCULATION OF RIVER RUNOFF TRANSPORT IN THE KARA SEA

Could wind drift transport river water from the estuary region to the southeastern coast of the Novaya Zemlya at about 75° N during the time period between the flood and expedition observations? How does runoff-induced stratification affect the velocity and direction of this drift? To answer these questions, we performed numerical experiments with the calculation of the trajectories of Lagrangian particles transported by wind-driven currents in the sea surface layer using actual wind speed data with and without consideration of the presence of a freshwater layer at the sea surface.

In numerical experiments, we used data on the wind velocity vector components at a height of 10 m.a.s.l., W_x and W_y, borrowed from the NCEP/NCAR Reanalysis meteorological database [7] (freely available at http://www.esrlnoaa.gov/psd/data/gridded/data.ncep.reanalvsis.html). These are time series of different meteorological parameters with the time step $\delta t = 6$ h for the period from 1948 to the present on a global grid with 2° longitude and latitude spacing. In calculations, data on a grid with 25 × 5 nodes for the Kara Sea and its environments in the range of 50°–96° E and 68°–78° N during the period from May 1 to November 1, 2007, were used. For each grid node, the time series W_x and W_y, 737 elements long with a time step of 6 h, were used. The period under consideration began before the spring flood and terminated after the end of the expedition of the R/V *Akademik Mstislav Keldysh* to the Kara Sea. The series of wind velocity components W_x and W_y were first recalculated into the series of wind velocity vector magnitude $W = \sqrt{W_x^2 + W_y^2}$ and direction φ_W ($\varphi_W = \arctan(W_y/W_x)$ at $W_x \geq 0$ and $\varphi_W = \arctan(W_y/W_x) + \pi$ at $W_x < 0$); wind velocity value was then recalculated into the wind friction velocity u_* from the empirical equation [8]

$$u_* = \sqrt{1.28 \times 10^{-3} c_D} W,$$
$$c_D \times 10^3 = \begin{cases} 1.14 & \text{at } W \leq 10 \text{ m/s}^{-1} \\ 0.49 + 0.065W & \text{at } W > 10 \text{ m/s}^{-1} \end{cases}, \quad (1)$$

where c_D is the resistance coefficient of the sea surface.

To calculate the trajectory of a Lagrangian particle occurring at a given moment at a point with coordinates (x, y), the friction velocity $u_*(x, y)$ and the wind direction $\varphi_W(x, y)$ at the same point at the same moment should be specified. The values of $u_*(x, y)$ and $\varphi_W(x, y)$ were calculated by the bilinear interpolation of the known u_* and φ_W values in the neighboring nodes of the grid to the given point (x, y) using the equation

$$F(x, y) = F(0,0)(1 - x)(1 - y) + F(1,0)x(1 - y) + F(1,1)xy + F(0,1)(1 - x)y, \quad (2)$$

where F is the interpolated function of two variables prescribed in the grid nodes (0, 0), (1,0), (0, 1), and (1, 1) at $0 \leq x \leq 1$ and $0 \leq y \leq 1$..

From the interpolated value of $u_*(x, y)$, the velocity vector value of the wind-driven current at the surface $V_S(x, y)$ and its angle of deviation from the wind direction $\varphi_S(x, y)$ were calculated. The new coordinates of the particle, (x_{j+1}, y_{j+1}) (where $j = 1, 2, 3, \ldots, 737$ is the time index with the time step $\delta t = 6$ h), were found from the equations

$$x_{j+1} = x_j + \delta t V_S(x_j, y_j) \cos[\varphi_W(x_j, y_j) + \varphi_S(x_j, y_j)], \quad (3)$$

$$y_{j+1} = y_j + \delta t V_S(x_j, y_j) \sin[\varphi_W(x_j, y_j) + \varphi_S(x_j, y_j)]. \quad (4)$$

The initial position of the particle was specified by a point with geographical coordinates of 78° E and 74° N (near the northern boundary of the Yenisei estuary) at 00:00 on June 1, 2007, which approximately corresponded to the beginning of the flood.

Four numerical experiments with different algorithms for calculating the surface drift velocity V_S and deviation angle φ_S depending on the friction velocity, the roughness parameter, the Coriolis parameter, and the freshwater layer thickness:

(1) The classical model of Ekman drift with the constant vertical eddy viscosity coefficient K and without consideration for the presence of a freshwater layer at the sea surface [6]. In this case, $\varphi_S = -\pi/4$, $V_S = u_*^2/\sqrt{Kf} = \sqrt{2} u_*/\kappa$, where f is the Coriolis parameter, and $\kappa = 0.4$ is the Karman constant. The latter equation was derived under the condition that $K = \kappa u_* L_E/2$ [1], where $L_E = \kappa u_*/f$ is the Ekman depth.

(2) The Madsen model [9] with a linear increase of the eddy viscosity coefficient with depth z in a purely turbulent flow at the sea surface $K = \kappa u_* z$ [4]. The values of $V_S = \sqrt{u_0^2 + v_0^2}$ and φ_S as functions of the friction velocity u_*, the roughness parameter h_S, and the Coriolis parameter f, without consideration for the presence of a freshwater layer, are found from the following expression:

$$u_0 + iv_0 = \frac{u_*}{\kappa}\left[\frac{\pi}{2} + i\left(-1.15 + \ln\frac{L_E}{z_0}\right)\right], \quad (5)$$

where $z_0 = h_S/30$, $i = \sqrt{-1}$ is the imaginary unit. A trial calculation was performed for the roughness parameter $h_S = 0.05$ m, as recommended by Madsen [9]. In a calculation using this model, the deviation angle of the surface drift from the wind direction was $\varphi_S \approx -10°$.

(3) The Price–Sundermeyer model [10], which presents a stationary freshwater layer as a surface layer of thickness h with a depth-constant eddy viscosity coefficient significantly exceeding its value in the lower layer. In [1], the solution obtained in [10] was reduced to dimensionless parameters on the surface ($z = 0$). In this case, the values of V_S and φ_S as functions off riction

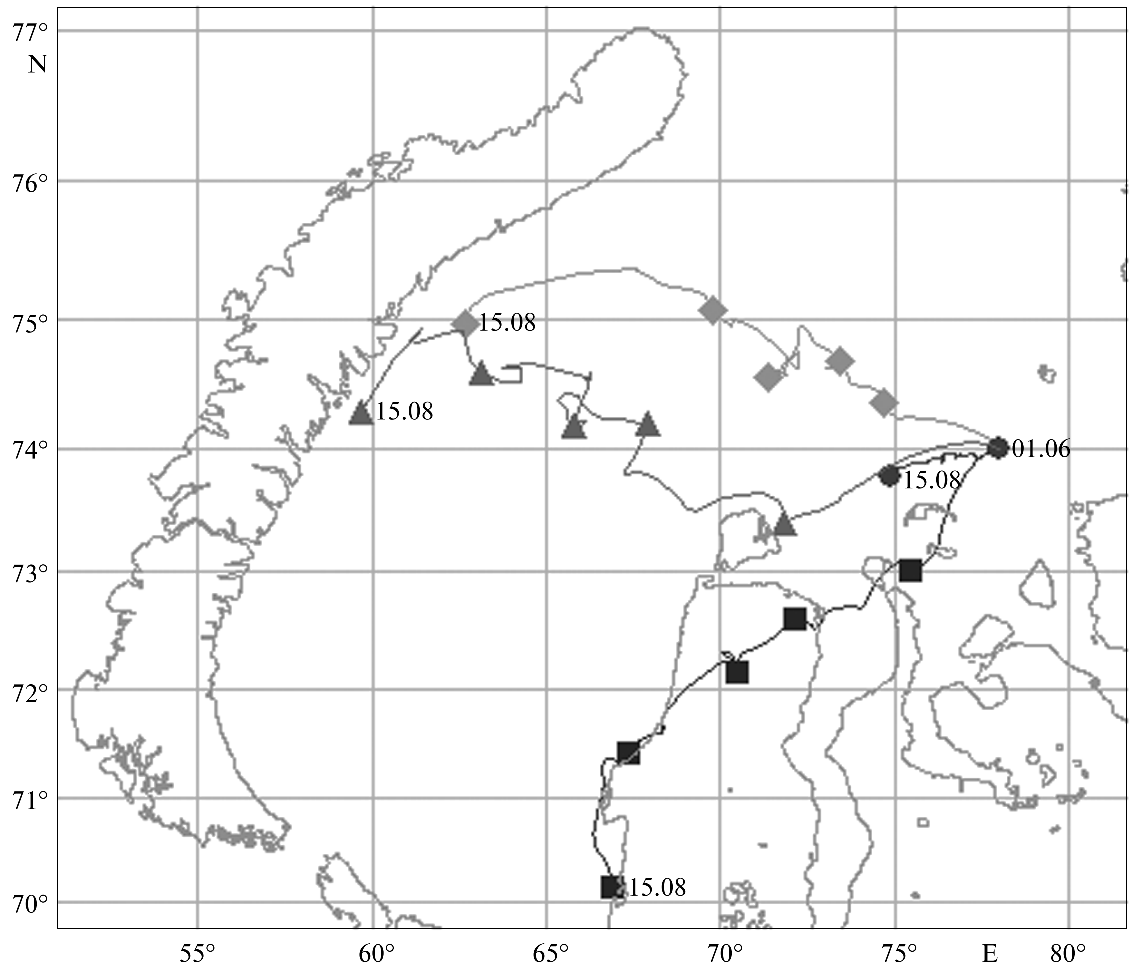

Fig. 2. Lagrangian particle trajectories calculated from different wind drift models. Particle positions with 15-day intervals: (circles) the classical Ekman wind drift model [6]; (black squares) the Madsen model [9]; (gray rhombs) the Price–Sundermeyer model [10]; (triangles) the model considering the effects of a surface freshwater layer in the sea revealed in [1]. Numbers indicate dates (day and month in 2007).

velocity u_*, freshwater layer thickness h, and the Coriolis parameter f are specified by the following equations:

$$\frac{V_S}{V_S(h=\infty)} = \lambda \frac{\sqrt{\exp(8\gamma) - 2\exp(4\gamma)\cos(4\gamma) + 1}}{\exp(4\gamma) - 2\exp(2\gamma)\cos(2\gamma) + 1}, \quad (6)$$

$$\varphi = -\arctan\left(\frac{\exp(4\gamma) + 2\exp(2\gamma)\sin(2\gamma) - 1}{\exp(4\gamma) - 2\exp(2\gamma)\sin(2\gamma) - 1}\right), \quad (7)$$

where $\gamma = \mathrm{E}^{-1/2}$, $\lambda = \mathrm{E}^{1/2}$ at $\mathrm{E} \geq 1$, and $\gamma = \mathrm{E}^{-1}$, $\lambda = 1$ at $\mathrm{E} < 1$, $\mathrm{E} = L_\mathrm{E}/h$ is the Ekman number; and $V_S(h=\infty) = u_*^2/\sqrt{Kf} = \sqrt{2}u_*/\kappa$ is the surface drift velocity value in a liquid of homogeneous density (according to the classical Ekman problem solution). Note that Eq. (6) shows an asymptotic behavior ($V_S \to \infty$ at $\mathrm{E} \to \infty$), which does not correspond to reality and significantly overestimates the values of V_S at $\mathrm{E} > 15$ [1]; therefore, it should be used with reserve. A trial calculation was performed for the freshwater layer thickness $h = 3$ m; at the friction velocity $u_* = 5.5 \times 10^{-3}$ m/s (average for the Kara Sea in summer of 2007 [2]) and $f = 1.4 \times 10^{-4}$ s^{-1}, this corresponds to a moderate value of the Ekman number $\mathrm{E} = 5.2$ (the reduction of the solution obtained in [10] to the dimensionless form, Eqs. (6)–(7), was described in more detail in [1]).

(4) A model taking into account the effect of stratification with the use of the reported simulation results for the evolution of the freshwater layer [1]. The two main effects of the freshwater layer on the wind drift revealed earlier [1] were seen: an increase in the drift current velocity by 1.4–2.6 times and a right turn of the current vector direction up to 50° compared to the undisturbed state (in the absence of stratification). Therefore, a trial calculation was performed with the drift velocity V_S found from Eq. (5) with a multiplier of 1.5 and the current direction turn $\varphi_S = -50°$ instead of $\varphi_S \approx -10°$ in the Madson model [9].

The results of calculating the trajectory of a Lagrangian particle according to the above four algorithms are given in Fig. 2.

The calculation with the classical Ekman drift predicted the transfer of the particle to less than 100 km to the west of the initial point during the period before the mid-August (when a northern wind prevailed). Calculations using the Madson model [9] showed the transport of the particle to a distance of about 600 km during the period from June 1 to August 15, but the movement was directed to the southwest rather than to Novaya Zemlya, where the lens was detected. It can be seen (Fig. 2) that a part of the trajectory calculated by this model passes overland (traverses the Yamal Peninsula): this is related to the fact that the proposed problem statement does not consider solid boundaries. Thus, both algorithms for the calculation of drift current without account for the upper freshwater layer provide no agreement with the observations.

Significantly different results were obtained in calculations using algorithms 3 and 4, which considered the effect of the freshwater layer on the wind drift. For the period between June 1 and August 15, 2007, both algorithms described the west transport of the Lagrangian particle with its approach to the Novaya Zemlya coast and reaching the position where the Yenisei water lens was observed. Thus, the localization of the freshwater lens observed at the eastern coast of the Novaya Zemlya in the early fall of 2007, between 74° and 76° N, may be attributed to the transport of the freshwater layer by drift currents with account for the effect of stratification on the wind velocity and direction.

3. CONCLUSIONS

The main conclusion from the numerical experiments performed is that the adequate consideration of the effect of the stratification caused by runoff at the sea surface on the wind drift velocity and direction is essential for the calculation of the transport of river runoff to the sea. The physical sense of this phenomenon is clear: the inflow of river water creates a freshwater layer on the sea surface, and the eddy exchange at its lower boundary is limited because of a stable density jump. Therefore, the energy transferred by the wind remains almost completely in this thin layer, which acquires a higher velocity than it would without stratification, where the energy would distribute over the entire water column. Thus, the classical Ekman relationships derived under the assumption of a depth-constant eddy viscosity coefficient and infinite ocean depth should significantly underestimate the drift velocity in this case, as was found in our calculations (numerical experiment 1). Attempts to involve some continuous dependence of the viscosity coefficient on the depth in consideration, as in the Madson model [9] (numerical experiment 2), do not improve the situation. However, the direct consideration of the freshwater layer, as in the Price–Sundermeyer model [10] or in our model [1], gives satisfactory results.

Calculations by means of algorithms accounting for the effect of density stratification created by the freshwater layer show a good agreement of the transport time and the location of Lagrangian particles derived from the model with the actual time and position of the river-water lens at the eastern coast of the Novaya Zemlya, between 74° and 76° N, observed in the expedition of the R/V *Akademik Mstislav Keldysh* to the Kara Sea in the early fall of 2007.

ACKNOWLEDGMENTS

This work was supported in part by the Russian Science Foundation, project no. 14-50-00095.

REFERENCES

1. N. V. Zhurbas, "The wind-induced drift velocity of the freshwater layer on the sea's surface," Oceanology (Engl. Transl.) **53** (2), 136–144 (2013).
2. 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 (Engl. Transl.) **50** (5), 657–667 (2010).
3. 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 (Engl. Transl.) **55** (4), 450–460 (2015).
4. A. S. Monin and A. M. Yaglom, *Statistical Hydromechanics. Mechanics of Turbulence* (Nauka, Moscow, 1965), Part 1.
5. B. Cushman-Roisin, *Introduction to Geophysical Fluid Dynamics* (Prentice Hall, Englewood Cliffs, NJ, 1994).
6. V. W. Ekman, "On the influence of the Earth's rotation on ocean currents," Arch. Math. Asron. Phys. **2** (11), 1–52 (1905).
7. E. Kalnay, M. Kanamitsu, R. Kistler, et al., "The NCEP/NCAR 40-year reanalysis project," Bull. Am. Meteorol. Soc. **77** (3), 437–471 (1996).
8. W. G. Large and S. Pond, "Open ocean momentum flux measurements in moderate to strong winds," J. Phys. Oceanogr. **11** (3), 324–336 (1981).
9. O. S. Madsen, "A realistic model of the wind-induced Ekman boundary layer," J. Phys. Oceanogr. **7** (2), 248–255 (1977).
10. J. F. Price and M. A. Sundermeyer, "Stratified Ekman layers," J. Geophys. Res., C: Oceans Atmos. **104** (9), 20467–20494 (1999).
11. J. E. Smith, *Torrey Canyon Pollution and Marine Life* (Cambridge University Press, Cambridge, 1968).
12. M. W. Stacey, S. Pond, and P. H. LeBlond, "A wind-forced Ekman spiral as a good statistical fit to low-frequency currents in coastal strait," Science **233**, 470–472 (1986).

Translated by K. Pankratova