DOI: 10.22449/2413-5577-2022-4-25-38

Vertical Mixing in the Black Sea Active Layer from Small-Scale Measurement Data

A. N. Morozov *, E. V. Mankovskaya

Marine Hydrophysical Institute of RAS, Sevastopol, Russia
**e-mail: anmorozov@mhi-ras.ru*

Abstract
The paper considers the methodological issues of using the G03 parameterization to estimate the vertical turbulent diffusion coefficient from current velocity and density stratification data collected with a depth increment of 4 m. Based on the expedition materials obtained during the 87th cruise of the R/V *Professor Vodyanitsky* (30 June to 18 July 2016) in the central sector of the northern Black Sea, this coefficient was estimated at the upper boundary of the cold intermediate layer and the depth layer of 350–390 m. The results of measurements in the acoustic Doppler current profiler exposure mode near the sea surface and at the lower sounding point were used as input data on the current velocity. In the upper sea layer at a potential density of 14.2 kg/m^3, the coefficient value was $7.26 \cdot 10^{-6}$ m^2/s, which is close to its value of $6 \cdot 10^{-6}$ m^2/s in the core of the cold intermediate layer estimated from the thermal conductivity equation from the 2017 expedition measurements. The corresponding heat flux into the cold intermediate layer is 1.79 W/m^2. An indirect estimate of the coefficient in the seasonal thermocline was $2.26 \cdot 10^{-7}$ m^2/s. This value is comparable to the molecular heat diffusion coefficient. Salt flux at a potential density value of 14.2 kg/m^3 is 2,977 $g/(m^2 \cdot year)$, the corresponding salt transport through the isopycnal surface is $1.1 \cdot 10^{15}$ g/year, or about 22 % of the mass of salt brought into the Black Sea by the lower Bosphorus current per year. In the layer of 350–390 m depth at a potential density value of about 16.9 kg/m^3, the estimated vertical turbulent diffusion coefficient was $2.66 \cdot 10^{-6}$ m^2/s. The corresponding heat flux was $3.9 \cdot 10^{-3}$ W/m^2, or about 10 % of the geothermal flux. Salt flux of 4.110^{-6} $g/(m^2/s)$ corresponds to its transport of $3.9 \cdot 10^{13}$ g/year through the isopycnal surface and represents 0.75 % of the mass of salt brought by the lower Bosphorus current per year. The ratio of the kinetic energy of small-scale processes to their potential energy was found to be 1.53 for the near-surface layer and 11 for the lower sounding point. This variability determines an almost threefold enhancement of vertical mixing at the upper measurement point according to the G03 parameterization

Keywords: Black Sea, vertical mixing, shear, strain, current velocity, heat flux, salt flux

Acknowledgements: the work was performed under state assignment no. 0555-2021-0003 on topics "Operational oceanology", no. 0555-2021-0005 "Coastal studies".

For citation: Morozov, A.N. and Mankovskaya, E.V., 2022. Vertical Mixing in the Black Sea Active Layer from Small-Scale Measurement Data. *Ecological Safety of Coastal and Shelf Zones of Sea*, (4), pp. 25–38. doi:10.22449/2413-5577-2022-4-25-38

Вертикальное перемешивание в деятельном слое Черного моря по данным мелкомасштабных измерений

А. Н. Морозов *, Е. В. Маньковская

Морской гидрофизический институт РАН, Севастополь, Россия
**e-mail: anmorozov@mhi-ras.ru*

Аннотация
Рассмотрены методические вопросы использования параметризации *G*03 для оценки коэффициента вертикальной турбулентной диффузии по данным о скорости течения и плотностной стратификации, собранным с разрешением 4 м по глубине. На основе экспедиционных материалов, полученных в 87-м рейсе НИС «Профессор Водяницкий», проходившем с 30 июня по 18 июля 2016 г. в центральном секторе северной части Черного моря, выполнена оценка значений этого коэффициента на верхней границе холодного промежуточного слоя и слое глубин 350–390 м. В качестве исходных данных о скорости течения были использованы результаты измерений в режиме выдержки акустического доплеровского профилометра течений у поверхности моря и в нижней точке зондирования. В верхнем слое моря при потенциальной плотности 14.2 кг/м^3 значение коэффициента составило $7.26 \cdot 10^{-6}$ м^2/с, что близко к его значению $6 \cdot 10^{-6}$ м^2/с в ядре холодного промежуточного слоя, оцененному из уравнения теплопроводности по результатам измерений экспедиций 2017 г. Соответствующий поток тепла в холодный промежуточный слой равен 1.79 Вт/м^2. Косвенная оценка коэффициента в сезонном термоклине составила $2.26 \cdot 10^{-7}$ м^2/с – значение, сопоставимое с коэффициентом молекулярной диффузии тепла. Поток соли при значении потенциальной плотности 14.2 кг/м^3 равен 2977 г/(м^2·год), соответствующий перенос соли через изопикническую поверхность – $1.1 \cdot 10^{15}$ г/год, или около 22 % массы соли, приносимой в Черное море нижнебосфорским течением за год. В слое глубин 350–390 м при значении потенциальной плотности около 16.9 кг/м^3 оценка коэффициента вертикальной турбулентной диффузии составила $2.66 \cdot 10^{-6}$ м^2/с. Соответствующий поток тепла равен $3.9 \cdot 10^{-3}$ Вт/м^2, или около 10 % геотермального потока. Поток соли $4.1 \cdot 10^{-6}$ г/(м^2·с) соответствует ее переносу через изопикническую поверхность в размере $3.9 \cdot 10^{13}$ г/год и составляет 0.75 % от массы соли, приносимой нижнебосфорским течением за год. Установлено отношение кинетической энергии мелкомасштабных процессов к их потенциальной энергии, которое равно 1.53 для верхнего слоя и 11 для нижней точки зондирования. Такая изменчивость определяет почти трехкратное усиление вертикального перемешивания в верхней точке измерений в соответствии с параметризацией *G*03.

Ключевые слова: Черное море, вертикальное перемешивание, сдвиг скорости течения скорость течения, поток тепла, поток соли

Благодарности: работа выполнена в рамках государственного задания по темам № 0555-2021-0003 «Оперативная океанология», № 0555-2021-0005 «Прибрежные исследования».

Для цитирования: *Морозов А. Н., Маньковская Е. В.* Вертикальное перемешивание в деятельном слое Черного моря по данным мелкомасштабных измерений // Экологическая безопасность прибрежной и шельфовой зон моря. 2022. № 4. С. 25–38. EDN TRZMDQ. doi:10.22449/2413-5577-2022-4-25-38

Introduction

Vertical fluxes of heat, salt, nutrients and other substances in the Black Sea water column have a significant impact on the functioning of the ecosystem of the upper active layer and partly determine the efficiency of reproduction of its resources used in the national economy (fishing, mussel farms, oyster plantations, etc.). Basically, vertical exchange is carried out by means of turbulent mixing. As a result, the estimation of the vertical turbulent diffusion coefficient in the Black Sea has been an urgent task of oceanology for many years [1)] [1–7].

The range of coefficient values given in the literature for the Black Sea extends from values close to the molecular heat diffusion coefficient of $\sim 10^{-7}$ m^2/s [3] to the maximum value of $3 \cdot 10^{-2}$ m^2/s (in the work [1)]). Such a large range of coefficient values is determined both by the difference in methods for its assessment, and by the spatio-temporal difference in hydrophysical conditions and atmospheric effects. At present, it is generally accepted that the value of the vertical turbulent diffusion coefficient obtained from microstructural data is the most reliable [4]. However, the sources only state two cases of using microstructural probes in the deep part of the Black Sea [3, 4], which give the values of the coefficient in the upper stratified layer of the sea at the level of $O(10^{-6})$ m^2/s. A small number of this kind of data is due to the high cost of equipment, technological difficulties in carrying out measurements and data processing. At the same time, synchronous measurements of density and current velocity profiles performed with a small-scale resolution are currently widespread and are often used to estimate the vertical turbulent diffusion coefficient [6, 8–12].

From the summer of 2016 to the present day, the Marine Hydrophysical Institute has carried out more than 20 expeditions in the central sector of the northern part of the Black Sea [13, 14], where both CTD measurements and measurements of current velocity profiles using the Acoustic Doppler Current Profilers (ADCP) were taken. The purpose of this work is to study the characteristics of small-scale processes in the active layer of the Black Sea. The article discusses methodological issues of applying the G03 parameterization [10, 11] for estimating the vertical turbulent diffusion coefficient based on the data obtained as a result of ADCP exposure near the sea surface and at the bottom of sounding. The measurement data are used to estimate the heat and salt fluxes at the upper boundary of the cold intermediate layer [13] and at the lower boundary of the upper layer of shear baroclinic currents [6, 15]. It is expected that the proposed approach to estimating the vertical turbulent diffusion coefficient, applied to the entire array of data collected during expeditions of recent years, will make it possible to assess the seasonal variability of the intensity of vertical mixing at different depths in the active layer of the Black Sea.

[1)] Blatov, A.S., Bulgakov, N.P., Ivanov, V.A., Kosarev, A.N. and Tuzhilkin, V.S., 1984. *Variability of Hydrophysical Fields of the Black Sea*. Leningrad: Gidrometeoizdat, 240 p. (in Russian).

Data, instruments and methods

The expedition materials obtained during the 87th cruise of the R/V *Professor Vodyanitsky*, which took place from 30.06.2016 to 8.07.2016 in the central sector of the northern part of the Black Sea (31°–36.5° E, 43°–45° N), were used in the article [16]. CTD measurements were performed using the SBE 911plus probe, the results were interpolated to a grid with a step of 1 m. The current velocity profiles were measured using a lowered ADCP based on WHM300 manufactured by RDI, depth resolution (*b*) 4 m [17]. The total number of stations was 106. The work used data from 65 stations taken at a sea depth of more than 400 m. The current velocity vectors in the 30–60 m layer at these stations are shown in Fig. 1. The stations were evenly located in the area of the Rim Current and outside it closer to the center of the sea. The sequence of measuring the current velocity profile included 3–5 min exposures of the instrument near the sea surface and at the lower sounding point [14]. It is the data obtained during ADCP exposures at these horizons that are analyzed in this work.

Density profiles ($\rho = 1000 + \sigma_\theta$, where σ_θ is the potential density, kg/m^3) were previously subjected to low-frequency depth filtering using a triangular filter corresponding to ADCP spatial averaging, transfer function $H_{ADCP}(k) = (\sin(\pi bk)/(\pi bk))^4$ (k is the vertical wave number) [17]. Further, using linear interpolation, the density values were determined at the horizons for measuring the current velocity.

Fig. 2 shows the initial data in the form of a scattering diagram: the buoyancy frequency square is plotted along the abscissa ($N^2 = (g/\rho)(\Delta\sigma_\theta/\Delta z)$, where g is the acceleration of gravity; Δz is the depth increment (here – 4 m)); along the y-axis, the squared shear of the current velocity according to the data ADCP ($Sh^2_{ADCP} = (\Delta U/\Delta z)^2 + (\Delta V/\Delta z)^2$, where U, V are the eastern and northern components

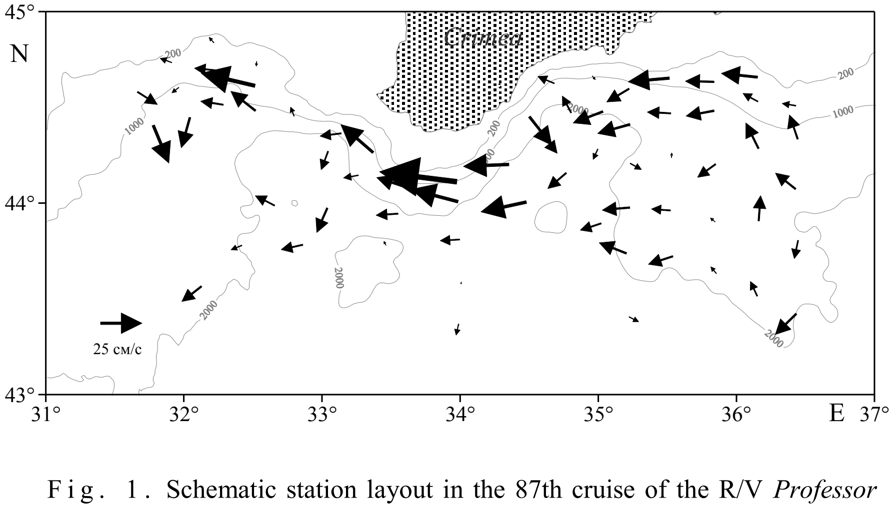


Fig. 1. Schematic station layout in the 87th cruise of the R/V *Professor Vodyanitsky* (arrows show current velocity vectors at the layer of 30–60 m)

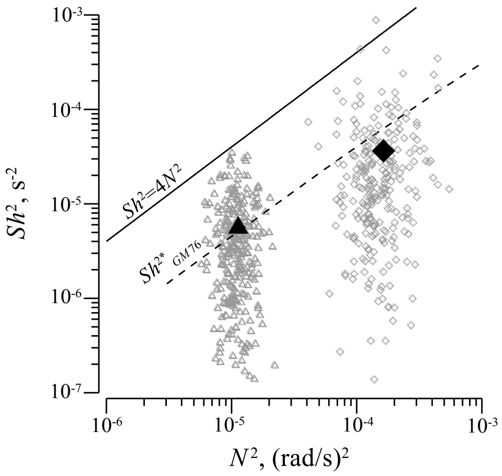


Fig. 2. Input data of CTD-soundings and ADCP measurements (grey diamonds are for the exposure near the sea surface, grey triangles are for that at the lower sounding point; black symbols – mean values)

of the current velocity vector). Transfer function of differentiation at a finite depth increment $H_{\mathrm{Dif}}(k) = (\sin(\pi\Delta zk)/(\pi\Delta zk))^2$ [18]. Gray diamonds correspond to the data obtained in the vicinity of the upper boundary of the cold intermediate layer (density 14.2 ± 0.15 kg/m^3) when the device is exposed near the sea surface. The number of readings is 256, the average depth of the isopycna with a potential density of 14.2 kg/m^3 is 44 m. The grey triangles correspond to the data collected when the instrument was exposed at the lower probing point. The number of readings is 566, the average density value is 16.9 kg/m^3, the average depth is 369 m. Black markers are average values $\langle N^2\rangle$ and $\langle Sh^2\rangle$, where $\langle\ldots\rangle$ is the operator of averaging over all samples.

The solid black line corresponds to the critical value of the gradient Richardson number (Ri = N^2/Sh^2), which is 0.25 [19]. At values of the Richardson number less than the critical one, a linear instability of the shear flow can occur, leading to the development of turbulence. It can be seen from the figure that in the initial data set, all values of the Richardson number at the lower sounding point are greater than the critical one, which can be perceived as the absence of turbulent mixing, since the necessary condition for shear flow instability is not met. This is due to the fact that the measurements were carried out with the spatial depth resolution inherent in ADCP and, in addition, the derivatives were calculated at finite depth increments. The vertical resolution of the shear measurement process, determined by the weakening of the transfer function $H_{ADCP}\cdot H_{\mathrm{Dif}}$ to a level of 3 dB, was about 12 m. It was shown in [20] that the enhancement of turbulence dissipation should be associated with small values of the Richardson number obtained at vertical increments of 3 m. At the same time, estimates of the value of the Richardson number on a 10-meter scale have little in common with the microstructure. In essence, this means that turbulence is mainly generated at vertical scales that are smaller than the vertical resolution with which our measurements were made.

The black dashed line represents the results of the ratio $Sh^{2*}_{GM76} = \int_0^1 F_{GM76}(N,k)\cdot H_{ADCP}(k)\cdot H_{\mathrm{Dif}}(k)\cdot dk$, where $F_{GM76}(N, k)$ – shear spectral density for the canonical spectrum of internal waves GM76 [21, 22], as given in [23]. At the upper boundary of the cold intermediate layer $\langle Sh^2_{ADCP} \rangle = 3.7 \cdot 10^{-5}$ s^{-2}; $Sh^{2*}_{GM76} = 6.2 \cdot 10^{-5}$ s^{-2}. This confirms the fact that the intensity of internal waves in the Black Sea is weaker than in oceanic conditions, for which the canonical spectrum of GM76 was determined. For the ocean, there are two sources of internal waves approximately equal in power: tides and wind [24], while in the Black tide-free sea, the only source of internal waves is the wind [25]. At the lower point of the sounding, the average value of the squared measured shear ($\langle Sh^2_{ADCP} \rangle = 5.5 \cdot 10^{-6}$ s^{-2}) slightly (10 %) exceeds the value of $Sh^{2*}_{GM76} = 5 \cdot 10^{-5}$ s^{-2}, which is a less expected result. Early parameterizations for estimating the vertical turbulent diffusion coefficient from the data collected at fine-scale resolution were based either on the Richardson number [26] or on the relationship $K_V \infty \left(\langle Sh^2_{ADCP} \rangle / Sh^{2*}_{GM76} \right)^2$ [8], or on a more complex dependence on the Richardson number and the probability of observing its value less than the critical one [27, 28].

Results and discussion

In the framework of this article, to estimate the coefficient of vertical turbulent diffusion (K_V), the parameterization G03 [10] was used, which takes into account the deviation of the spectrum of internal waves from the canonical form [9] and the geographical location of the measurement area. The applied formulas for calculations are borrowed from [11]:

$$K_V = K_0 \frac{\langle Sh^2_{ADCP} \rangle^2}{\left(Sh^2_{GM76} \right)^2} \cdot h_1(R_\omega) \cdot j\left(\frac{f}{N} \right),$$

$$h_1(R_\omega) = \frac{3(R_\omega + 1)}{2\sqrt{2} R_\omega \sqrt{R_\omega - 1}},$$

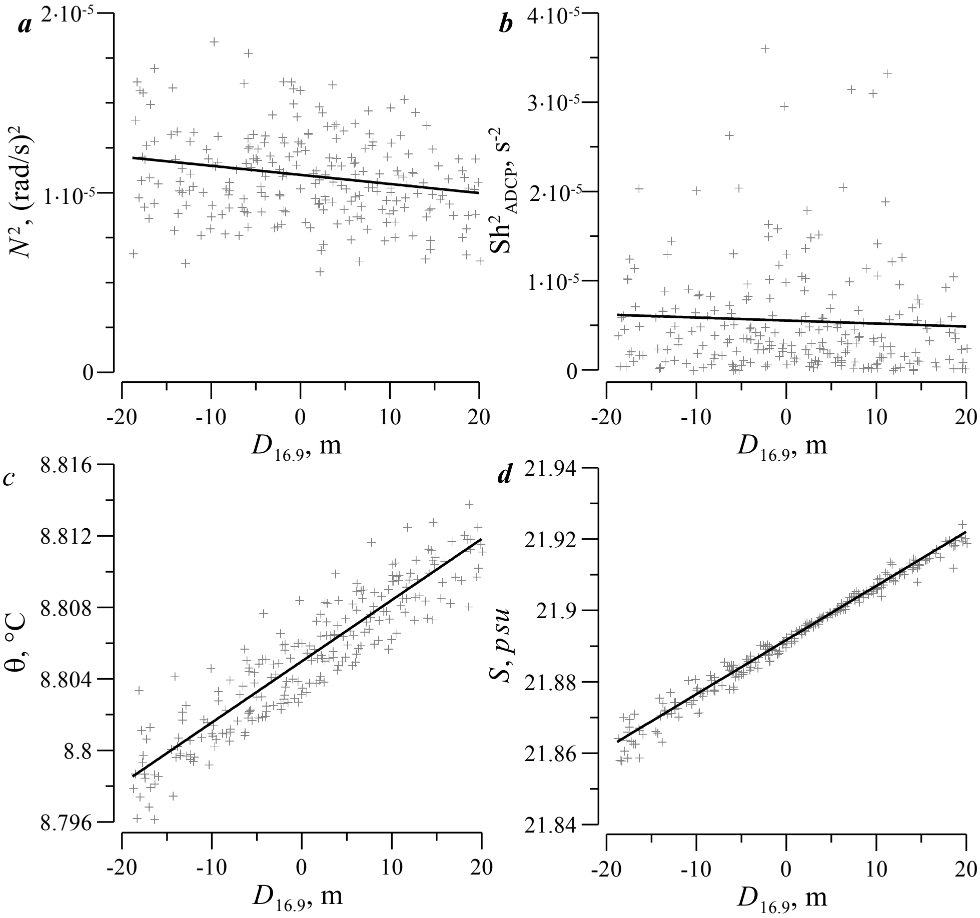
$$j(f/N) = \frac{f \operatorname{arccos} h(N/f)}{f_{30} \operatorname{arccos} h(N_0/f_{30})},$$

where $K_0 = 5 \cdot 10^{-6}$ m^2/s; f is the local inertial frequency at 44° N; f_{30} is the inertial frequency at 30° N; $N_0 = 5.24 \cdot 10^{-3}$ rad/s. The ratio of flow velocity shear to strain variations (R_ω – the shear/strain variance ratio), or the ratio of kinetic and potential energy of small-scale processes, is defined as

$$R_\omega = \frac{\langle Sh^2_{ADCP} \rangle}{\langle N^2 \rangle \langle \xi^2_Z \rangle},$$

where $\langle \xi^2_z \rangle = \langle \delta^2 \rangle / \langle N^2 \rangle^2 = \langle (N^2 - N^2_{\text{Fit}})^2 \rangle / \langle N^2 \rangle^2$ is the mean square strain; N_{Fit} is the dependence characterizing stable features of density stratification.

Lower boundary of the upper layer of shear baroclinic currents. Fig. 3 shows some graphical material explaining the procedure for estimating the coefficient of vertical turbulent diffusion and calculating the heat and salt fluxes based on the data obtained at the lower point of sounding. Fig. 3, *a* shows the dependence of the buoyancy frequency square on the difference between the measurement depth and the isopycnal depth σ_θ = 16.9 kg/m^3 ($D_{16.9}$).The linear dependence N^2_{Fit} on distance was drawn by the least squares method (black line) and characterizes the stable state of density stratification. The normalized value of deformation at $D_{16.9} = 0$ $\langle Sh^2_{\text{Strain}} \rangle = \langle \xi^2_z \rangle \cdot \langle N^2 \rangle \approx 5 \cdot 10^{-7}$ rad^2/s^2, while the mean value of the square of the measured shear of the current velocity at $D_{16.9} = 0$



F i g . 3 . Dependences of buoyancy frequency square (*a*); square of ADCP shear (*b*); temperature (*c*); salinity (*d*) on the distance to isopicna σ_θ = 16.9 kg/m^3 in the range of ±20 m. Crosses are for input data, black lines are for dependences

$\langle Sh^2_{ADCP} \rangle \approx 5.5 \cdot 10^{-6}$ s^{-2} (Fig. 3, *b*). The ratio of kinetic horizontal energy to potential energy $R_\omega = 11$, which is close to the estimate of this parameter for the 250–500 m layer in the Black Sea given in [5]. For spectrum GM76 $R_\omega = 3$. A significant difference in the values of the parameter is caused by the dominance of internal waves in the deep layers of the Black Sea near the inertial range [14, 29–31], which are more pronounced in the horizontal current velocity than in the deformation of isopycnal surfaces. Values of the parameter R_ω, which is in the range of 8–14, are also characteristic of the northern seas [32], and in some areas of the Atlantic Ocean, R_ω reaches 100 [12]. The value of the function $h_1(R_\omega) = 0.37$, which is ~ 2.5 times less than that for the canonical spectrum GM76. The calculated value of the coefficient $K_V = 2.66 \cdot 10^{-6}$ m^2/s, which is only ~ 2 times less than modern theoretical predictions [7], and ~ 60 times less than that given in earlier works [1, 2].

The salt flux was calculated from the ratio $F_{\text{Salt}} = \rho \cdot K_V \cdot S_Z$, where $S = \partial S/\partial z = 1.5 \cdot 10^{-3}$ psu/m is the salinity derivative (S) with respect to depth (Fig. 3, *d*). The corresponding value $F_{\text{Salt}} = 4.1 \cdot 10^{-6}$ g/(m^2·s). Assuming that the area of the horizontal section of the sea at a depth of 370 m is equal to $3 \cdot 10^5$ km^2 [33], we find that the salt flux amounting to $3.9 \cdot 10^{13}$ g/year rises through it. The lower Bosphorus current brings an average of 150 km^3 (V_B) of Marble Sea water with a salinity of about 34 psu [33] to the Black Sea, or about $5.1 \cdot 10^{15}$ g/year of salt. Thus, through the isopycnal surface $\sigma_\theta = 16.9$ kg/m^3, the amount of salt, which is 0.75 % of its inflow through the Bosphorus Strait against 35 % given in [3] rises. In other words, to maintain the salt balance, it is necessary that less than one percent of the salt brought by the lower Bosphorus current penetrate into the depth layer of more than 350 m.

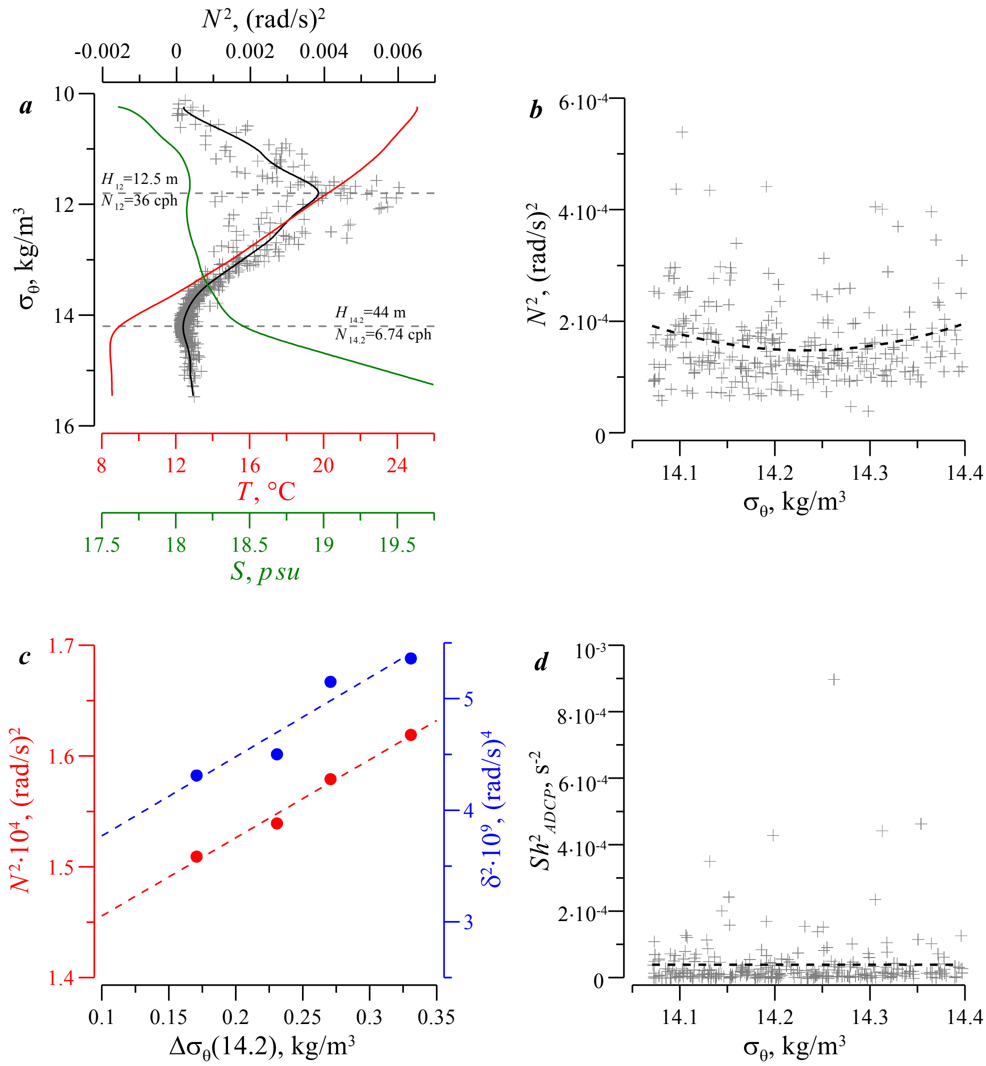
The heat flux was calculated from the relation $F_{\text{Heat}} = \rho \cdot C_W \cdot K_V \cdot \theta_z$, where $C_W = 4.2 \cdot 10^3$ J/(°C·kg) is the heat capacity of water; $\theta_z = \partial\theta/\partial z = 3.4 \cdot 10^{-4}$ °C/m is the derivative of potential temperature (θ) with respect to depth (Fig. 3, *c*). The corresponding value $F_{\text{Heat}} = 3.9 \cdot 10^{-3}$ W/m^2, which is about 10 % of the geothermal heat flux ($F_{\text{HeatGeo}} = 40$ mW/m^2 [34, 35]). At an average water temperature of the lower Bosphorus current of 14 °C, the Black Sea receives $F_{\text{HeatBosph}} = \rho \cdot C_W \cdot (T_M - T_0) \cdot V_B = 9 \cdot 10^{18}$ J/year, at $T_0 = 0$ °C. $F_{\text{Heat16.9}} = 3.7 \cdot 10^{16}$ J/year and is transferred through the isopycnal surface with a potential density of 16.9 kg/m^3, which is about 0.41 % of the heat supplied with the lower Bosphorus current.

The almost twofold excess of the share of the salt flux (0.75 %) over the share of the heat flux (0.41 %) can be explained by the difference in the processes of exchange of substances with the environment when the waters of the Marble Sea are submerged to depths of more than 370 m. In particular, heat exchange occurs not only with the surrounding aquatic environment, but also through the bottom surface.

Upper boundary of the cold intermediate layer. Calculation of the vertical turbulent diffusion coefficient from the data obtained during ADCP exposure near the sea surface was carried out according to a complicated procedure. This is due to the fact that the characteristic scales of stable stratification variability are close to the vertical resolution of the measurements.

The temperature and salinity profiles (Fig. 4, *a*) were obtained as a result of low-frequency filtering of the initial data and were subsequently used to determine the corresponding vertical derivatives. The largest number of measurements N^2 is observed in the vicinity of the local minimum of the buoyancy frequency between the seasonal and permanent pycnocline at potential density values of 14.2 ± 0.15 kg/m^3 (256 readings in Fig. 4, *a* and *b*) [13]. In order to minimize the influence of the final resolution of measurements on the determination of parameters $\langle \delta^2 \rangle$ and $\langle N^2 \rangle$, their calculation was made for several samples of initial data falling into windows of different widths ($\Delta\sigma_\theta$) with symmetrical boundaries relative to the value of potential density $\sigma_\theta = 14.2$ kg/m^3. In the calculation of $\langle \delta^2 \rangle$, stable stratification was represented by a second-order polynomial (dashed line in Fig. 4, *b*). The results of the determinations were well represented by linear dependences obtained by the least squares method with a decrease in the sampling window width from 0.35 to 0.15 kg/m^3 (corresponding dashed lines in Fig. 4, *c*). The lower threshold of the window width was determined from the condition that the amount of initial data should be at least 100. Further in the calculations, we used the values $\delta^2(0)$ and $N^2(0)$ obtained from the linear dependences at $\Delta\sigma_\theta = 0$. The average value of the squared shear did not show any dependence on the width of the sampling window. The measured value of the squared normalized deformation was about 1.2 of its value for the spectrum of GM76. On the contrary, the measured value of the squared shear of the current velocity (Fig. 4, *d*) is only about 0.6 of its value for the spectrum of GM76. The corresponding ratio of the kinetic and potential energies of small-scale processes $R_\omega = 1.53$, which is almost two times less than its value for the spectrum of GM76. This can be caused by the interaction of internal waves with vertical inhomogeneities of stable density stratification, which have characteristic scales close to the lengths of internal waves. The function value $h_1(R_\omega) = 2.53$ versus units for GM76 spectrum. Geographic correction $j = 1.55$. Vertical turbulent diffusion coefficient $K_V = 7.26 \cdot 10^{-6}$ m^2/s, which is quite close to its value ($\sim 6 \cdot 10^{-6}$ m^2/s) in the core of the cold intermediate layer at $\sigma_\theta = 14.5$ kg/m^3, calculated from the heat conduction equation [13].

The heat flux through the isopycnal surface with a potential density of 14.2 kg/m^3 ($F_{\text{Heat14.2}}$) was 1.79 W/m^2, which significantly exceeds the value of the geothermal flux. At a qualitative level, it is obvious that the seasonal pycnocline in the Black Sea weakens the exchange processes between the upper homogeneous mixed layer and the water column, but quantitative estimates are rarely given in the literature [36]. By equating the heat fluxes at the upper boundary of the cold intermediate layer and in the seasonal pycnocline, we can estimate the vertical turbulent mixing coefficient in the seasonal pycnocline itself from the relation $K_V(12) \approx T_z(14.2)/T_z(12) \cdot K_V(14.2) = 2.26 \cdot 10^{-7}$ m^2/s. The obtained value is close to the value of the heat molecular diffusion coefficient ($k_T = 1.4 \cdot 10^{-7}$ m^2/s). In essence, this means that in summer the heat flux from the upper homogeneous mixed layer into the water column through the seasonal thermocline is largely determined by molecular diffusion.



F i g . 4 . Averaged profiles of temperature (red line), salinity (green line), and buoyancy frequency square (black line, crosses are for input data) (*a*); dependence of buoyancy frequency square on density in the neighbourhood of value 14.2 kg/m^3 (crosses are for input data, dashed line is for quadratic polynomial approximant) (*b*); dependences of buoyancy frequency square (red dots) and mean squared deviation from the mean (blue dots) on the sampling window width in the neighbourhood of density value of 14.2 kg/m^3 (dashed lines are for approximating linear dependences) (*c*); dependence of squared shear on density (dashed line is for the mean) (*d*)

The microstructural measurements taken in the Yellow Sea with similar parameters of the pycnocline also showed values of the vertical turbulent diffusion coefficient comparable to the molecular heat diffusion coefficient [37].

The salt flux through the isopycnal surface at the value of potential density σ_0 = 14.2 kg/m^3 is equal to 2977 g/(m^2·year), which gives a salt transfer of 1.1·10^{15} g/year. This is about 22 % of the salt flow brought into the Black Sea by the lower Bosphorus current. A significant violation of the salt balance can be explained by the seasonal variability of both the exchange through the Bosphorus Strait [34] and the vertical turbulent diffusion coefficient [6].

Conclusion

The methodological issues of applying the G03 parametrization for estimating the vertical turbulent diffusion coefficient from the current velocity and stratification data collected near the sea surface and at the lower point of sounding with a small-scale resolution are considered.

For the upper boundary of the cold intermediate layer at a potential density of 14.2 kg/m^3, the corresponding estimate of the coefficient was 7.26·10^{-6} m^2/s. This is close to its value in the core of the cold intermediate layer (6·10^{-6} m^2/s) obtained from the heat transfer equation based on the results of several expeditions in 2017. The corresponding vertical heat flux was 1.79 W/m^2. The salt transfer through the isopycnal surface with a potential density of 14.2 kg/m^3 is 1.1·10^{15} g/year, or about 22 % of the mass of salt (5.1·10^{15} g/year) brought into the Black Sea by the lower Bosphorus current. An indirect estimate of the coefficient in the seasonal pycnocline amounts to 2.26·10^{-7} m^2/s and shows its comparability with the heat molecular diffusion coefficient, which is in good agreement with the results of microstructural measurements for similar conditions.

For the lower boundary of shear baroclinic flows at a potential density of 16.9 kg/m^3, the estimate of the vertical turbulent diffusion coefficient was 2.66·10^{-6} m^2/s, which is almost half the size of the theoretical estimate. The corresponding heat flux is 3.9·10^{-3} W/m^2, or ~10 % of the geothermal heat flux. A salt flux of 4.1·10^{-6} g/(m^2·s) corresponds to its transport through the isopycnal surface in the amount of 3.9·10^{13} g/year and is 0.75% of the mass of salt brought by the lower Bosphorus current per year.

One of the results of the presented work is the establishment of the ratio of kinetic and potential energy of small-scale processes. Near the surface in the vicinity of the isopycna with a potential density of 14.2 kg/m^3, its value amounted to 1.53 and 11 for the lower sounding point at a potential density of 16.9 kg/m^3. As a result, the value of the vertical turbulent diffusion coefficient at the surface turned out to be three times higher than at the lower point of sounding, despite the fact that the ratio of the buoyancy frequency square to the squared shear in the lower layer is almost half the size.

The given estimates of the parameters are conditional, but nevertheless they can be useful in discussing their values obtained by other methods, in particular, from the results of numerical experiments.

REFERENCES

1. Kolesnikov, A.G. and Boguslavskii, S.G., 1978. On the Vertical Transport in the Black Sea. In: MHI, 1978. *Marine Hydrophysical Research*. Sevastopol: MHI. Iss. 2, pp. 33–46. (in Russian).
2. Boguslavsky, S.G., Zhorov, V.A. and Ivashchenko, I.K., 1994. Formation of the Vertical Salinity Profile in the Black Sea. *Physical Oceanography*, 5(6), pp. 443–449. https://doi.org/10.1007/BF02198510
3. Gregg, M.C. and Yakushev, E., 2005. Surface Ventilation of the Black Sea's Cold Intermediate Layer in the Middle of the Western Gyre. *Geophysical Research Letters*, 32(3), L03604. doi:10.1029/2004GL021580
4. Zatsepin, A.G., Golenko, N.N., Korzh, A.O., Kremenetskii, V.V., Paka, V.T., Poyarkov, S.G. and Stunzhas, P.A., 2007. Influence of the Dynamics of Currents on the Hydrophysical Structure of the Waters and the Vertical Exchange in the Active Layer of the Black Sea. *Oceanology*, 47(3), pp. 301–312. https://doi.org/10.1134/S0001437007030022
5. Morozov, A.N. and Lemeshko, E.M., 2014. Estimation of Vertical Turbulent Diffusion Coefficient by CTD/LADCP-Measurements in the Northwestern Part of the Black Sea in May, 2004. *Morskoy Gidrofizicheskiy Zhurnal*, (1), pp. 58–67 (in Russian).
6. Podymov, O.I., Zatsepin, A.G. and Ostrovsky, A.G., 2017. Vertical Turbulent Exchange in the Black Sea Pycnocline and its Relation to Water Dynamics. *Oceanology*, 57(4), pp. 492–504. https://doi.org/10.1134/S0001437017040142
7. Samodurov, A.S., Chukharev, A.M. and Kazakov, D.A., 2021. Basic Regularities of Vertical Turbulent Exchange in the Mixed and Stratified Layers of the Black Sea. *Physical Oceanography*, 28(4), pp. 376–391. doi:10.22449/1573-160X-2021-4-376-391
8. Gregg, M.C., 1989. Scaling Turbulent Dissipation in the Thermocline. *Journal of Geophysical Research: Oceans*, 94(C7), pp. 9686–9698. https://doi.org/10.1029/JC094iC07p09686
9. Polzin, K.L., Toole, J.M. and Schmitt, R.W., 1995. Finescale Parameterizations of Turbulent Dissipation. *Journal of Physical Oceanography*, 25(3), pp. 306–328. https://doi.org/10.1175/1520-0485(1995)025<0306:FPOTD>2.0.CO;2
10. Gregg, M., Sanford, T. and Winkel, D., 2003. Reduced Mixing from the Breaking of Internal Waves in Equatorial Waters. *Nature*, 422, pp. 513–515. https://doi.org/10.1038/nature01507
11. Kunze, E., Firing, E., Hummon, J.M., Chereskin, T.K. and Thurnherr, A.M., 2006. Global Abyssal Mixing Inferred from Lowered ADCP Shear and CTD Strain Profiles. *Journal of Physical Oceanography*, 36(8), pp. 1553–1576. https://doi.org/10.1175/JPO2926.1
12. Ferron, B., Kokoszka, F., Mercier, H. and Lherminier, P., 2014. Dissipation Rate Estimates from Microstructure and Finescale Internal Wave Observations along the A25 Greenland–Portugal OVIDE Line. *Journal of Atmospheric and Oceanic Technology*, 31(11), pp. 2530–2543. https://doi.org/10.1175/JTECH-D-14-00036.1
13. Morozov, A.N. and Mankovskaya, E.V., 2020. Cold Intermediate Layer of the Black Sea According to the Data of Field Research in 2016-2019. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 5–16. doi:10.22449/2413-5577-2020-2-5-16 (in Russian).
14. Morozov, A.N. and Mankovskaya, E.V., 2021. Modern Studies of Water Dynamics in the North-Western Part of Black Sea from LADCP Measurements. In: MSU, 2021. *InterCarto. InterGIS. GI Support of Sustainable Development of Territories: Proceedings of the International conference*. Moscow: Faculty of Geography MSU. Vol. 27, part 3, pp. 5–15. doi:10.35595/2414-9179-2021-3-27-110-120

15. Morozov, A.N., Lemeshko, E.M., Shutov, S.A., Zima, V.V. and Deryushkin, D.V., 2017. Structure of the Black Sea Currents Based on the Results of the LADCP Observations in 2004–2014. *Physical Oceanography*, (1), pp. 25–40. doi:10.22449/1573-160X-2017-1-25-40

16. Morozov, A.N. and Mankovskaya, E.V., 2019. Seasonal Variability of Currents Structure in the Black Sea Northern Part from Field Measurements in 2016. *Fundamental and Applied Hydrophysics*, 12(1), pp. 15–20. https://doi.org/10.7868/S2073667319010027 (in Russian).

17. Morozov, A.N. and Lemeshko, E.M., 2006. Methodical Aspects of the Application of Acoustic Doppler Current Profilers in the Black Sea. *Physical Oceanography*, 16(4), pp. 216–233. https://doi.org/10.1007/s11110-006-0027-8

18. Morozov, A.N., 2018. Statistic of the Richardson Number according to Observations from the Oceanographic Platform. *Ecological Safety of Coastal and Shelf Zones of Sea*, (2), pp. 39–46. doi:10.22449/2413-5577-2018-2-39-46 (in Russian).

19. Miles, J., 1961. On the Stability of Heterogeneous Shear Flows. *Journal of Fluid Mechanics*, 10(4), pp. 496–508. doi:10.1017/S0022112061000305

20. Toole, J. and Schmitt, R., 1987. Small-Scale Structures in the North-West Atlantic Sub-Tropical Front. *Nature*, 327, pp. 47–49. https://doi.org/10.1038/327047a0

21. Garrett, C. and Munk, W., 1975. Space-Time Scales of Internal Waves: A Progress Report. *Journal of Geophysical Research*, 80(3), pp. 291–297. https://doi.org/10.1029/JC080i003p00291

22. Cairns, J.L. and Williams, G.O., 1976. Internal Wave Observations from a Midwater Float, 2. *Journal of Geophysical Research*, 81(12), pp. 1943–1950. https://doi.org/10.1029/JC081i012p01943

23. Fer, I., 2006. Scaling Turbulent Dissipation in an Arctic Fjord. *Deep Sea Research Part II: Topical Studies in Oceanography*, 53(1–2), pp. 77–95. https://doi.org/10.1016/j.dsr2.2006.01.003

24. Munk, W. and Wunsch, C., 1998. Abyssal Recipes II: Energetics of Tidal and Wind Mixing. *Deep Sea Research Part I: Oceanographic Research Papers*, 45(12), pp. 1977–2010. https://doi.org/10.1016/S0967-0637(98)00070-3

25. Morozov, A.N., Mankovskaya, E.V. and Fedorov, S.V., 2021. Inertial Oscillations in the Northern Part of the Black Sea Based on the Field Observations. *Fundamentalnaya i Prikladnaya Gidrofzika*, 14(1), pp. 43–53. doi:10.7868/S2073667321010044 (in Russian).

26. Munk, W.H. and Anderson, E., 1948. Notes on a Theory of the Thermocline. *Journal of Marine Research*, 7(3), pp. 276–295.

27. Kunze E., Williams III, A.J. and Briscoe, M.G., 1990. Observations of Shear and Vertical Stability from a Neutrally Buoyant Float. *Journal of Geophysical Research: Oceans*, 95(C10), pp. 18127–18142. https://doi.org/10.1029/JC095iC10p18127

28. Polzin, K., 1996. Statistic of the Richardson Number: Mixing Models and Finestructure. *Journal of Physical Oceanography*, 26(8), pp. 1409–1425. https://doi.org/10.1175/1520-0485(1996)026<1409:SOTRNM>2.0.CO;2

29. Morozov, A.N., 2001. Spectral Parameters of Inertial Oscillations in the Black Sea. In: MHI, 2001. *Ekologicheskaya Bezopasnost' Pribrezhnoy i Shel'fovoy Zon i Kompleksnoe Ispol'zovanie Resursov Shel'fa* [Ecological Safety of Coastal and Shelf Zones and Comprehensive Use of Shelf Resources]. Sevastopol: MHI. Iss. 2, pp. 61–69 (in Russian).

30. Klyuvitkin, A.A., Ostrovskii, A.G., Lisitzin, A.P. and Konovalov, S.K., 2019. The Energy Spectrum of the Current Velocity in the Deep Part of the Black Sea. *Doklady Earth Sciences*, 488(2), pp. 1222–1226. https://doi.org/10.1134/S1028334X1910012X
31. Khimchenko, E., Ostrovskii, A., Klyuvitkin, A. and Piterbarg, L., 2022. Seasonal Variability of Near-Inertial Internal Waves in the Deep Central Part of the Black Sea. *Journal of Marine Science and Engineering*, 10(5), 557. https://doi.org/10.3390/jmse10050557
32. Naveira Garabato, A.C., Oliver, K.I.C., Watson, A.J. and Messias, M.-J., 2004. Turbulent Diapycnal Mixing in the Nordic Seas. *Journal of Geophysical Research: Oceans*, 109(C12), C12010. https://doi.org/10.1029/2004JC002411
33. Ivanov, V.A. and Belokopytov, V.N., 2013. *Oceanography of the Black Sea*. Sevastopol, 210 p.
34. Kutas, R.I., 2010. Geothermal Conditions of the Black Sea Basin and Its Surroundings. *Geophysical Journal*, 32(6), pp. 135–158 (in Russian).
35. Stanev, E.V., Chtirkova, B. and Peneva, E., 2021. Geothermal Convection and Double Diffusion Based on Profiling Floats in the Black Sea. *Geophysical Research Letters*, 48(2), e2020GL091788. https://doi.org/10.1029/2020GL091788
36. Morozov, A.N., Ivanov, V.A., Shutov, S.A., Zima, V.V., Deryushkin, D.V. and Lemeshko, E.M., 2016. Spatial Structure of Currents near Gerakleysky Peninsula According ADCP-Observations in 2015. In: MHI, 2016. *Ecological Safety of Coastal and Shelf Zones of Sea*. Sevastopol: MHI. Iss. 16, pp. 73–79 (in Russian).
37. Liu, Zh., Wei, H., Lozovatsky, I.D. and Fernando, H.J.S., 2009. Late Summer Stratification, Internal Waves, and Turbulence in the Yellow Se. *Journal of Marine Systems*, 77(4), pp. 459–472. https://doi.org/10.1016/j.jmarsys.2008.11.001

Submitted 26.09.2022; accepted after review 25.10.2022;
revised 02.11.2022; published 23.12.2022

About the authors:

Alexey N. Morozov, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), Ph. D. (Tech.), **ORCID ID: 0000-0001-9022-3379**, **Scopus Author ID: 7202104940, ResearcherID: ABB-4365-2020**, *anmorozov@mhi-ras.ru*

Ekaterina V. Mankovskaya, Senior Research Associate, Marine Hydrophysical Institute of RAS (2 Kapitanskaya St., Sevastopol, 299011, Russian Federation), Ph. D. (Tech.), **ORCID ID: 0000-0002-4086-1687**, **Scopus Author ID: 57192647961, ResearcherID: AAB-5303-2019**, *emankovskaya@mhi-ras.ru*

Contribution of the authors:

Alexey N. Morozov – problem setting; processing, analysis and description of the study results; preparation of the article text and graphics

Ekaterina V. Mankovskaya – measurement data processing; collection of information to study; discussion of results; article text correction

All the authors have read and approved the final manuscript.