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Original article

Vertical Mixing in the Main Pycnocline of the Black Sea in Summer

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Abstract
Purpose. The study is aimed at assessing the parameters of vertical turbulent mixing in the main pycnocline of the Black Sea based on the data on current velocity and density measured by standard hydrological instruments.
Methods and Results. The data collected during six summer cruises of R/V *Professor Vodyanitsky* in the central sector of the northern sea area in 2016–2021 were used in the research. Temperature, salinity and current velocity profiles were measured by the CTD/LADCP probes. The vertical turbulent diffusion coefficient was calculated with the G03 parameterization. The applied relations are given. The values of the required parameters on the isopycnal surface with the conditional density value 15 kg/m^3 are used as the initial data. Their filtered dependencies on its depth are substituted into the calculated relations. It is found that a well-pronounced maximum of specific kinetic energy is observed on average when the isopycnal depth is 77 m. The values of the shear/strain ratio and the canonical internal wave spectrum are close. The average value of the measured shear constitutes about one third of the value of the canonical internal wave spectrum. The average value of the vertical turbulent diffusion coefficient is 10^{-6} m^2/s. Its value in the central sea area is comparable to the heat molecular diffusion coefficient. At the isopycnal depth 90 m the maximum value reaching $1.6 \cdot 10^{6}$ m^2/s, is shifted to the right relatively the Rim Current at a horizontal distance of about 26 km. The average value of the turbulent kinetic energy dissipation rate is $2 \cdot 10^{-9}$ W/kg.
Conclusions. The value of the vertical turbulent diffusion coefficient calculated based on the data collected with a depth resolution of about 10 m agrees well with the estimates obtained from the data of microstructure probes. However, the results of the study should be considered preliminary; in order to obtain a more convincing confirmation of their correctness, it is advisable to conduct synchronous measurements using the microstructure probes and standard hydrological instruments.

Keywords: Black Sea, main pycnocline, vertical turbulent mixing, Rim Current, current velocity shear, strain

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Introduction

In a stratified marine environment, vertical turbulent mixing is the primary mechanism of diapycnal exchange of heat, salt, and other substances [1]. It plays a crucial role in water mass transformation, maintaining stratification and modulating large-scale circulation [2]. Currently, numerical modeling is one of the most important tools for studying the marine environment. However, the vertical resolution of modern models is insufficient to directly account for vertical mixing directly and requires parameterization [3]. The need for a deeper understanding of the impact of vertical mixing on biogeochemical processes, and for improving its parameterization in numerical models, highlights the importance of *in situ* studies.

For the experimental assessment of vertical mixing parameters, measurements with centimeter-scale vertical resolution are required [4]. However, the current use of microstructure profilers, which can achieve this level of resolution, is limited due to the high cost of the equipment and the significant time investment required for the measurements [5]. Microstructure measurements have only been conducted three times in the deep-water part of the Black Sea [1, 6, 7]. Measurements taken in March 2003 in the center of the western gyre [6] revealed that, in the oxycline, the values of the vertical turbulent diffusion coefficient (K_v) were as low as $(1-4)\cdot10^{-6}$ m²/s. A single profile obtained in July 2005 in the northeastern part of the sea [1] showed K_v value of approximately $4\cdot10^{-6}$ m²/s in the main pycnocline. Measurements conducted in August 2022 in the northern part of the central sector of the sea showed a minimum K_v value in the main pycnocline [7]. Unfortunately, the presentation format of the results does not allow for precise determination.

An alternative approach to estimating vertical mixing parameters uses density and current velocity profiles with a vertical resolution of about 10 meters. Such data are abundant for the Black Sea. In particular, these include measurements from the *Aqualog* probe [8], which was deployed at a depth of approximately 300 meters near Gelendzhik. The temporal variability of K_v vertical structure was studied using these data by applying a parameterization based on Richardson number values [9, 10]. Additionally, velocity profiles obtained using a lowered acoustic Doppler current profiler (LADCP) from a drifting vessel enabled the mean vertical structure K_v to be derived in the Sevastopol anticyclone region [11] and the northern part of the sea [12].

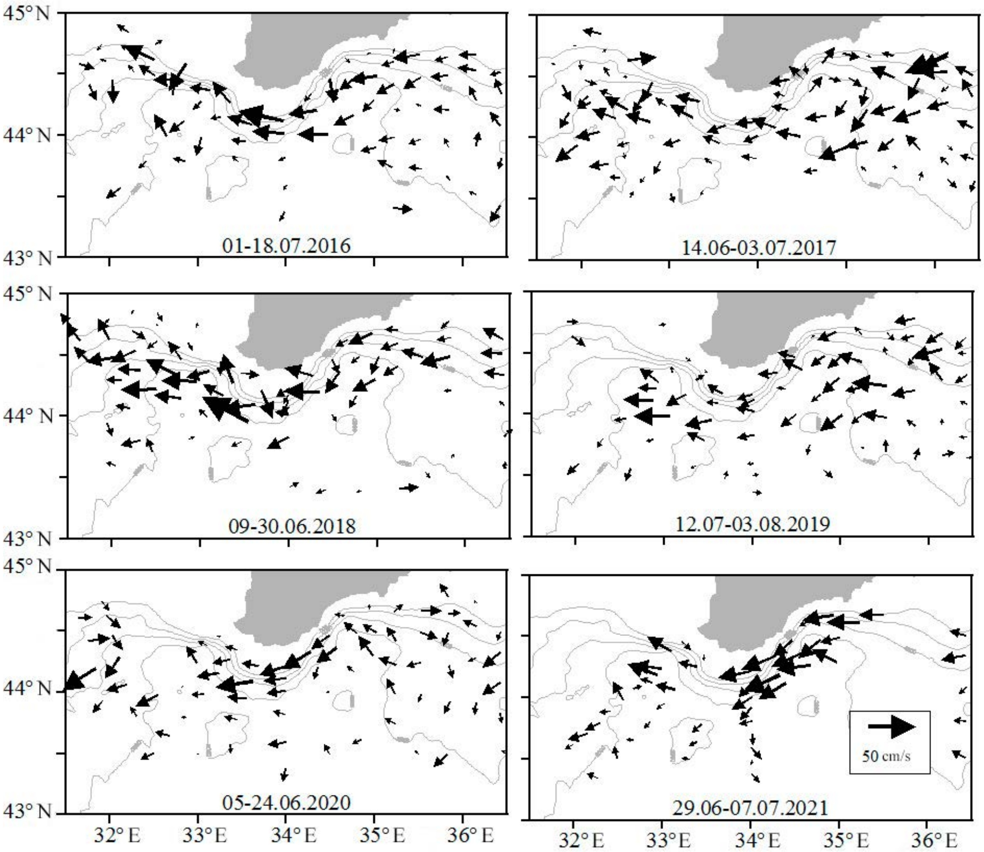
In this study, we analyze data collected during summer expeditions of the Marine Hydrophysical Institute [13] to examine the horizontal distribution of vertical turbulent mixing parameters within the main pycnocline. This issue remains unexplored to date, although there is a need to address it, particularly to improve our understanding of how large-scale dynamics affect vertical mixing processes. The G03 parameterization [14] was applied to estimate the vertical turbulent mixing parameters. This approach originated from theoretical work [15], followed by the practical application of its results [16, 17]. It was further developed in [18] and presented in its final form in [19]. The widespread use of the G03 parameterization today stems from its strong agreement with estimates derived from microstructure measurements [4, 5, 20, 21, 22].

This study aims to assess the parameters of vertical turbulent mixing in the main pycnocline of the Black Sea using current velocity and density data obtained from standard hydrological instruments.

Instruments and data

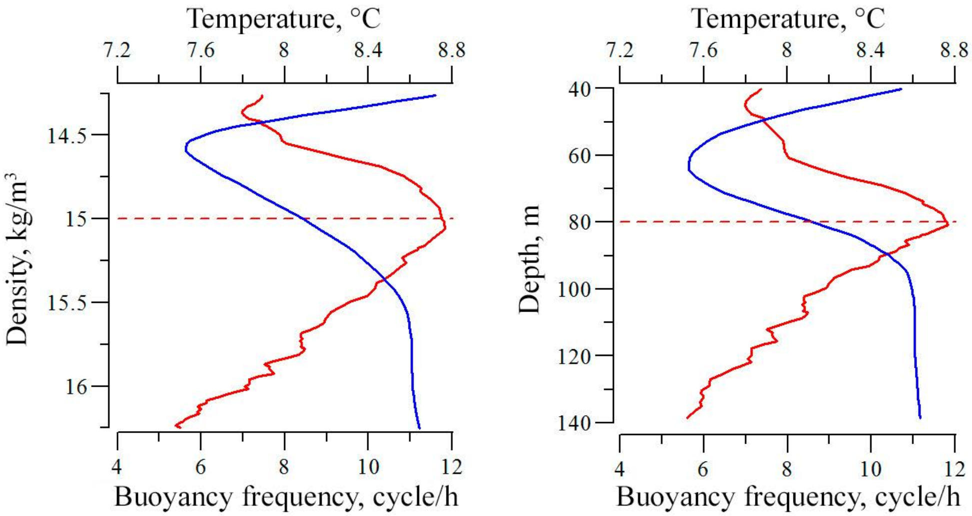
This study utilizes temperature, salinity, and current velocity profiles obtained during six summer research cruises of R/V *Professor Vodyanitsky* in the northern Black Sea (31.5–36.5°E, 43.5–45.0°N), between: 1–18 July 2016; 14 June – 3 July 2017; 9–30 June 2018; 12 July – 3 August 2019; 5–24 June 2020 and

29 June – 7 July 2021. The area covered by the sampling stations was non-uniform and varied from expedition to expedition (Fig. 1). The average inter-station distance was ~ 20 km. Temperature and salinity profiles were collected using a SBE911+ probe until 2019 and an Idronaut Ocean Seven 320 PlusM probe from 2019 onwards. Current velocity profiles were acquired using a lowered acoustic Doppler current profiler (LADCP) based on the WHM300 model. Setup parameters of the instrument were as follows: depth segment size – 4 m; broadband operating mode; descent/ascent speed: ~ 0.5 m/s.



F i g. 1. Current velocity measured at the 20 m depth during six summer cruises of R/V *Professor Vodyanitsky*. The arrow beginning corresponds to the station position (353 stations in total)

Large-scale cyclonic circulation is manifested by a predominance of westward currents (Fig. 1), with maximum values observed over the continental slope near the Southern Coast of Crimea. The Black Sea Rim Current (RC) is not clearly expressed, which can be explained by two factors. Firstly, it usually weakens during the summer months. Secondly, its jet width is approximately 30 km. With a spacing of approximately 20 km between sampling stations, it may not always be evident in the measurements. Mesoscale eddies were detected in two of the six expeditions. During the 2017 expedition, the Crimean anticyclone, centered at 34.78°E, 44.35°N with a diameter of approximately 60 km, was observed. During the 2020 expedition, a fragment of the Sevastopol anticyclone, centered at 31.6°E, 44.34°N with a similar diameter, was identified.



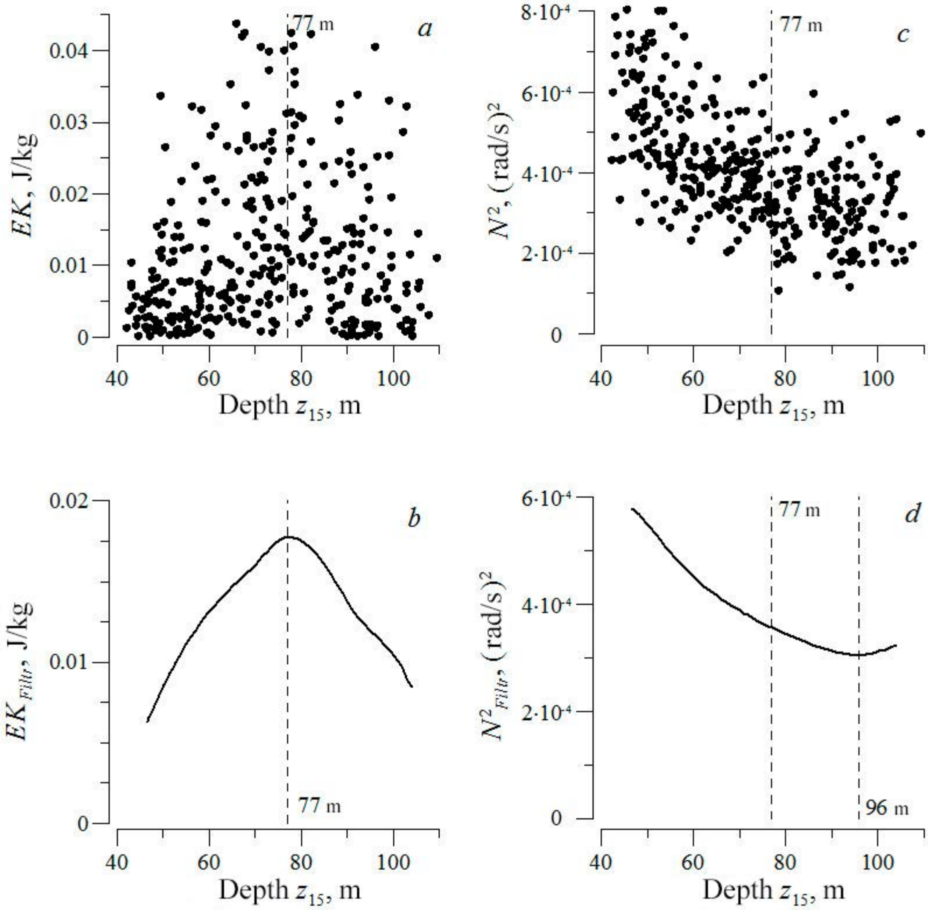
F i g. 2. Along-isopycnic averaged dependencies of water temperature (blue lines) and buoyancy frequency (red lines) upon density (*left*) and depth (*right*) during the cruise in 2017

Due to the cyclonic nature of a large-scale circulation in the Black Sea, its isopycnal surfaces are dome-shaped. Their depth increases from the center of the sea towards the continental slope. The depth difference between the center of the sea and the continental slope can reach 70 m or more. Therefore, to correctly understand the characteristic features of the mean vertical distribution of hydrological parameters and other environmental factors in the marine environment, isopycnal averaging should be performed. In the present study, special attention is given to determining the parameters of vertical turbulent mixing at a specific isopycnal surface. To select the conditional density value (σ_t), isopycnal averaging of buoyancy frequency profiles was performed for a set of stations from each expedition. The isopycnal relationships between buoyancy frequency and density averaged over the 2017 expedition (Fig. 2, left) reveal a pronounced maximum at σ_t = 15 kg/m³. Data from other expeditions confirm the presence of this maximum [13]. The isopycna with a conditional density value of 15 kg/m³ was selected for assessing diapycnal mixing parameters. One might intuitively expect enhanced density stratification at this isopycnal surface to lead to weakened vertical turbulent mixing. The isopycnal averaged temperature profiles shown in Fig. 2 demonstrate the relative position of the Cold Intermediate Layer, the best-known feature of the Black Sea's vertical thermal structure [13].

Results and discussion

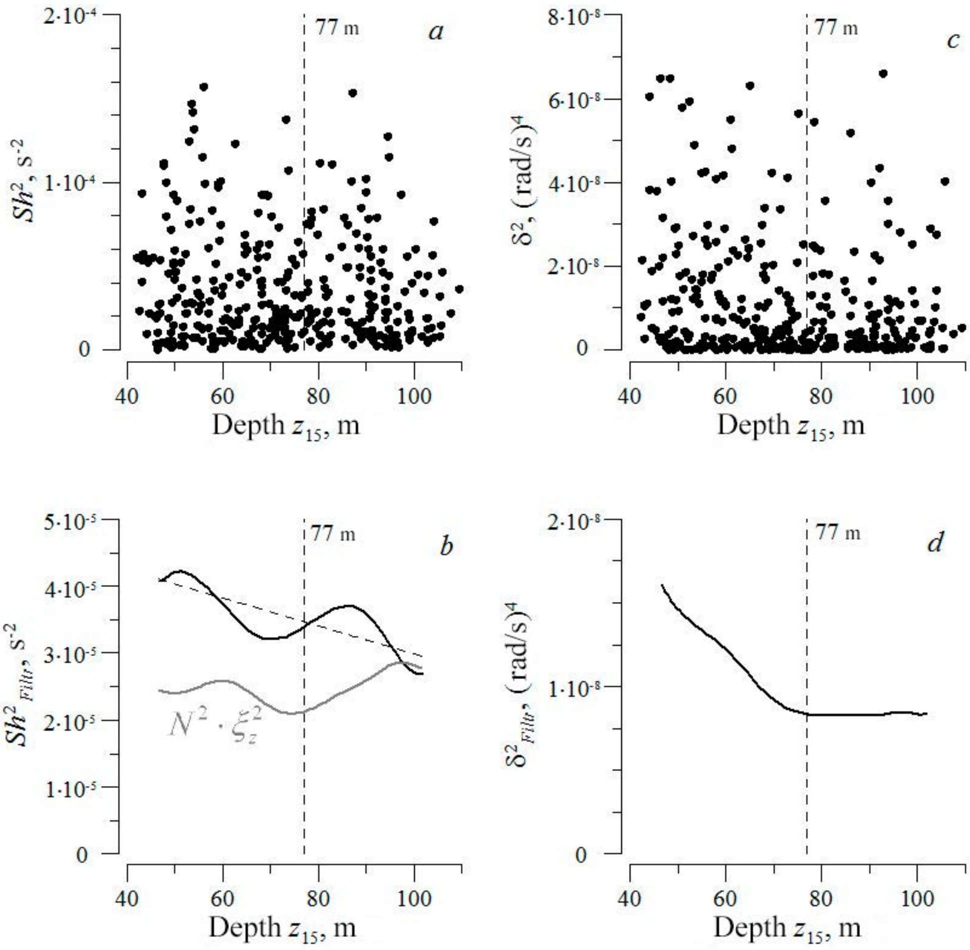
The values of hydrological parameters on the σ_t = 15 kg/m³ isopycnal surface were calculated for all 353 stations using linear interpolation. Low-frequency filtering of the raw data was performed using a cosine filter with a window width of

30 meters. The horizontal-to-vertical gradient ratio for the σ_t = 15 kg/m³ isopycnal surface depth was approximately 2 km per 1 m [23]. The following discussion focuses on the dependence of parameters on the isopycnal surface σ_t = 15 kg/m³ upon its depth (z_{15}).



F i g. 3. Dependencies of kinetic energy and square of buoyancy frequency (*a*, *c* – initial data; *b*, *d* – after filtration) on isopycnic surface σ_t = 15 kg/m^3 upon depth

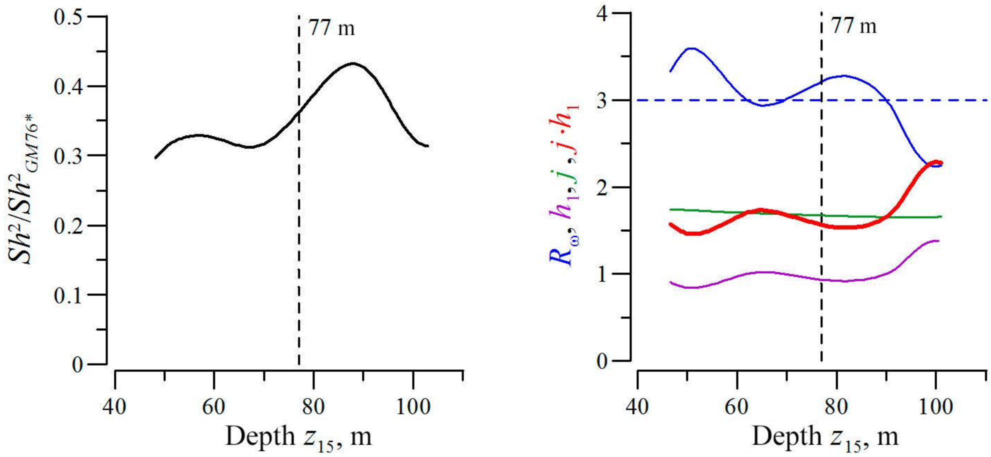
Fig. 3, a shows the relationship between the measured values of specific kinetic energy (*EK*) and the depth of the isopycnal surface with a conditional density of σ = 15 kg/m^3. The considerable scatter in the raw data (Fig. 3, *a*) may be partially attributed to the temporal variability of the current velocity field since the measurements were conducted in different years, as well as to internal waves with frequencies close to the local inertial frequency since each expedition lasted at least 30 inertial periods. Following filtering (Fig. 3, *b*), the dependence $EK_{Filtr}(z_{15})$ reveals a well-defined maximum at $z_{15} = 77$ m, with a current velocity magnitude of 19 cm/s at this maximum. This velocity maximum is associated with the Black Sea Rim Current (RC); its center is typically observed at $z_{15} = 77$ m (dashed line with 77 m marker in Figs. 3–6).



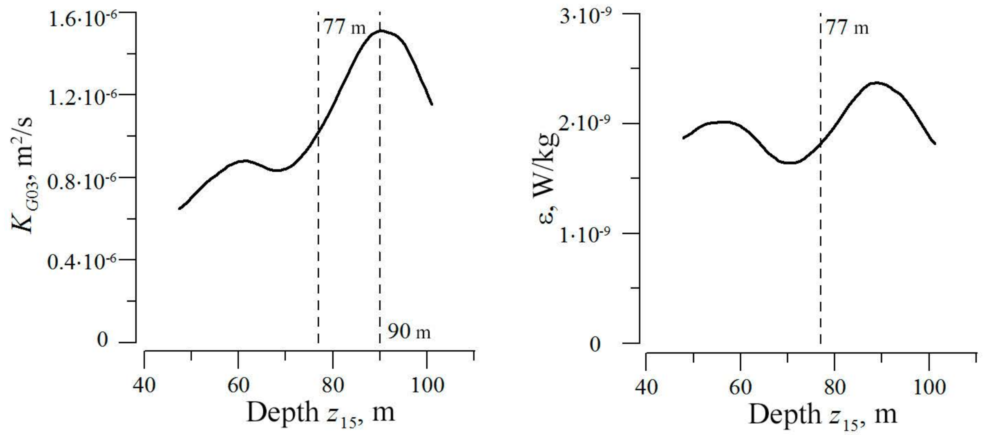
F i g. 4. Dependencies of shear square and buoyancy frequency anomaly square (*a*, *c* – initial data; *b*, *d* – after filtration) on isopycnal surface σ_t = 15 kg/m^3 upon depth. The grey line on fragment *b* is the ratio of square of buoyancy frequency anomaly to its square

Fig. 3, *c* shows the dependence of the measured square of buoyancy frequency values ($N^2 = \frac{g}{\rho}\rho_z$, where g is the gravitational acceleration; ρ is the density and ρ_z is its depth derivative) on depth z_{15}. The same filtered dependence is presented in Fig. 3, *d*. The buoyancy frequency decreases nearly monotonically from ~ 14 cycles/hour in the center of the sea to ~ 10 cycles/hour near the continental slope. A weakly pronounced minimum is observed at $z_{15} = 96$ m.

The dependence of the measured squared velocity shear ($Sh^2 = U_z^2 + V_z^2$, where U_z and V_z are the depth derivatives of the eastward and northward current velocity components, respectively) on depth z_{15} (Fig. 4, *a*) exhibits the characteristics of a random process. This is understandable, given that velocity shear is primarily determined by internal waves, whose spatiotemporal scales are significantly smaller than the dimensions of the survey area and the measurement intervals. After filtering (Fig. 4, *b*), the dependence shows decreasing shear values from the center of the sea towards the continental slope. The nearly harmonic component of the dependence, with a horizontal wavelength of approximately 70 km (35 m by depth z_{15}), may result from specific data sampling. Alternatively, this harmonic component may be generated by dynamic processes induced by the RC in its transverse direction. Further discussion of this issue based on the available data would be speculative.



F i g. 5. Dependency of the ratio of measured shear square to *GM*76* shear square on isopycnal surface σ_t = 15 kg/m^3 upon its depth (left), and dependencies of *G*03 parameterization multipliers on isopycnal surface σ_t = 15 kg/m^3 upon its depth (right)



F i g. 6. Dependencies of vertical turbulent diffusion coefficient (left) and dissipation rate of turbulent kinetic energy (right) on isopycnal surface σ_t = 15 kg/m^3 upon its depth

The square of deformation is determined from the relationship given in [18]:

$$\xi_z^2 = \frac{(N^2 - N_{Pol}^2)^2}{N_{Pol}^4} = \frac{\delta^2}{N_{Pol}^4},$$

where N_{Pol}^2 is the third-degree polynomial approximation of dependence $N^2(z_{15})$, calculated separately for station groups from each expedition, and a combined dataset was formed for all expeditions; $\delta^2 = (N^2 - N_{Pol}^2)^2$ is the squared buoyancy frequency anomalies (Fig. 4, *c*). Similar to velocity shear, the $\delta^2(z_{15})$ dependence exhibits characteristics of a random process. After filtering, the $\delta_{Filtr}^2(z_{15})$ dependence shows decreasing values from the center of the sea to the RC core, with nearly constant values between the RC and continental slope. The product $N^2\,\xi_z^2 = \delta_{Filtr}^2 / N_{Filtr}^2$ characterizes the potential energy of small-scale processes and, like velocity shear, contains a harmonic component with a wavelength of about 70 km (Fig. 4, *b*, grey line).

The empirical formulas from the work [19] are given below:

$$K_{G03} = K_0 \cdot \left(\frac{Sh_{Filtr}^2}{Sh_{GM76*}^2}\right)^2 \cdot h_1(R_\omega) \cdot j\left(\frac{f}{N_{Filtr}}\right),$$

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

$$j(f/N_{Filtr}) = \frac{f \operatorname{arc} h(N_{Fit}/f)}{f_{30} \operatorname{arc} h(N_0/f_{30})},$$

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; Sh_{GM6}^2 value was calculated for the canonical GM76 internal wave spectrum, taking into account the vertical resolution of LADCP current velocity measurements, as described in [24]:

$$Sh_{GM76*}^2 = \int_0^{100} \Phi_{Sh\_GM76}(k) \cdot H_{ADCP}(k) \cdot H_{Dif\_ADCP}(k) \cdot H_{DP\_ADCP}(k) \cdot dk,$$

where $\Phi_{Sh\_GM76}(k)$ is the velocity shear spectrum for the GM76 spectrum in the vertical wavenumber space (k); $H_{ADCP}(k) = (\mathrm{Sin}(\pi 4k)/(\pi 4k))^4$ is the spatial averaging transfer function characteristic of ADCP measurements; $H_{Dif\_ADCP}(k) = (\mathrm{Sin}(\pi 4k)/(\pi 4k))^2$ is the differentiation transfer function for a depth increment of 4 m; $H_{DP\_ADCP}(k) = (\mathrm{Sin}(\pi 4k)/(\pi 4k))^4$ is the window-type filtering transfer function used during data processing. The shear-to-strain ratio $R_\omega = \frac{Sh^2}{N^2 \cdot \xi_z^2}$ is interpreted as the ratio of the kinetic to the potential energy of internal waves and equals 3 for the GM76 spectrum. This value was calculated by accounting for the differences in the depth-averaging transfer functions when processing density and current velocity data, according to the following relationship:

$$R_\omega \approx \frac{Sh_{GM76}^2}{N_{Filtr}^2 \cdot \xi_{z\,GM76}^2} \cdot \frac{Sh_{Filtr}^2 / Sh_{GM76*}^2}{\xi_z^2 / \xi_{z\,GM76*}^2} = 3 \cdot \frac{Sh_{Filtr}^2 \cdot N_{Filtr}^2}{\delta_{Filtr}^2} \cdot \frac{N_{Filtr}^2 \cdot \xi_{z\,GM76*}^2}{Sh_{GM76*}^2},$$

where $\xi^2_{ZGM76*} = \int_0^{100} \Phi_{\xi_{z\_GM76}}(k) \cdot H_{Dif\_CTD} \cdot (k) \cdot H_{DP\_CTD}(k) \cdot dk$; $\Phi_{\xi_{z\_GM76}}(k)$ is the deformation spectrum of GM76; $H_{Dif\_CTD}(k) = (\mathrm{Sin}(\pi 4k)/(\pi 4k))^2$ is the differentiation transfer function at a depth increment of 4 m; $H_{DP\_CTD}(k) = = (\mathrm{Sin}(\pi 1k)/(\pi 1k))^4$ is the transfer function of CTD data processing. After appropriate integration, we obtain the ratio used in the calculations: $R_\omega \approx 2.1 \cdot \frac{Sh^2_{Filtr} \cdot N^2_{Filtr}}{\delta^2_{Filtr}}$.

The average ratio of the square of the measured velocity shear to Sh^2_{GM76*} shear (Fig. 5, left) is 0.35, showing no distinct features in the RC region (the maximum is located 20 km to the right of this region). This mean value appears realistic, given that wind serves as the sole source of internal waves in the non-tidal Black Sea and the study specifically examines summer conditions. The dependence $R_\omega(z_{15})$ (the blue line in Fig. 5, right) closely matches the values of the canonical internal wave spectrum (the blue dashed line in Fig. 5, right). Near the continental slope, the shear-to-strain ratio decreases to 2.2. The coefficient h_1, which is a function of the shear-to-strain ratio, shows a sharp increase as it approaches the continental slope. The latitude- and buoyancy-frequency-dependent coefficient j exhibits a slight decrease from the center of the sea towards its periphery (the green line in Fig. 5, right).

The parameter $K_{G03}(z_{15})$ varies from $6.5 \cdot 10^{-7}$ m²/s at z_{15} = 50 m to a maximum of $1.5 \cdot 10^{-3}$ m²/s at $z_{15} =$ 90 m (Fig. 6, left). In the central part of the sea, the values of the vertical turbulent diffusion coefficient are comparable to the molecular heat diffusion coefficient ($1.4 \cdot 10^{-7}$ m²/s). The maximum value is offset 26 km horizontally (23 m vertically) to the right of the Black Sea Rim Current (RC) and is presumably associated with anticyclonic eddies, which exhibit intensified vertical mixing in their cores. The relatively low values obtained for the vertical turbulent mixing coefficients (on average 10^{-6} m²/s) may be questionable, yet they show good agreement with microstructure profiler data [1, 6]. A more accurate comparison of vertical mixing parameters between fine-scale and microstructure measurements requires additional synchronous observations. The turbulent kinetic energy dissipation rate, calculated from the Osborn relation $\varepsilon = K_{G03} \cdot N^2_{Filtr}/0.2$, averages $2 \cdot 10^{-9}$ W/kg and contains a harmonic component with a wavelength of approximately 70 km (Fig. 6, right). The obtained ε value is typical for many regions of the World Ocean.

Conclusion

This study utilized density and current velocity profiles obtained during six summer research cruises of R/V *Professor Vodyanitsky* in the northern Black Sea between 2016 and 2021. Vertical turbulent mixing parameters were determined using the G03 parameterization. The filtered dependencies of the required parameters on the isopycnal surface with a conditional density value of 15 kg/m^3 were used as input data for the depth. The resolution capabilities of the density and current velocity sensors were considered during the integration of the canonical internal wave spectrum.

The presence of a buoyancy frequency maximum was confirmed on the isopycnal surface, which had a conditional density value of 15 kg/m³. Analysis revealed a well-defined maximum in specific kinetic energy occurring at the mean depth of this isopycnal surface (77 m).

It was found that the values of the squares of the current velocity shear and buoyancy frequency anomaly values on the specified isopycnal surface decreased from the center of the sea to the continental slope. The shear and deformation dependencies reveal a distinct harmonic component with a horizontal wavelength of approximately 70 km, oriented perpendicular to the RC. The square of the measured shear is approximately one third of that of the internal wave canonical spectrum. The shear-to-strain ratio in the center of the sea is approximately equal to the ratio of the canonical spectrum of internal waves, decreasing to 2.3 near the continental slope.

The mean value of the vertical diffusion coefficient on the isopycnal surface at σ_t = 15 kg/m³ during the summer period is 10^{-6} m²/s, which shows good agreement with estimates from a microstructure profiler. In the central part of the sea, the coefficient values are comparable to those of molecular thermal diffusivity. The maximum coefficient value is observed at a depth of 90 m on the isopycnal surface and reaches $1.6 \cdot 10^{-6}$. This maximum is offset approximately 26 km to the right of the RC, corresponding roughly to the radius of a mesoscale anticyclonic eddy. The mean turbulent kinetic energy dissipation rate is $2 \cdot 10^{-9}$ W/kg.

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