Vertical Structure of Current Velocity Shears in the Main Pycnocline of the Black Sea Based on the *in situ* Data in 2016

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The characteristic features of the averaged vertical structure of the current velocity shears are discussed based on the analysis of the LADCP/CTD data collected in three expeditions of the R/V "Professor Vodyanitsky" in the northern Black Sea in 2016: the 87th cruise (June, 30 – July, 18); the 89th cruise (September, 30 – October, 20) and the 91st cruise (November, 16 – December, 5). The maximum of the shear average profile is noted in the main pycnocline layer in the vicinity of the buoyancy frequency maximum. The ratio of the shear mean square to the buoyancy frequency mean square increases almost monotonously with depth from 0.1 to 0.4 in the layer 50–350 m that can indicate (at a qualitative level) relative intensification of turbulent vertical mixing in the lower part of the main pycnocline. The mean profiles of the shear vector rotation angle relative to its direction on the horizon 15 m are given. On the average, the shear vector rotates clockwise and makes about two rotations in the main pycnocline layer. The revealed rotation of the shear vector is due to influence of the internal waves propagating downward at the close to inertial frequency. The hodographs of the current velocity shear exhibiting a well-pronounced rotation with depth are shown. Considered is the example of calculating the parameters of a near-inertial internal wave using the current velocity shear and deformation based on the data of one of the stations.

Keywords: vertical shears of current velocity, vertical turbulent mixing, main pycnocline, the Black Sea, LADCP.

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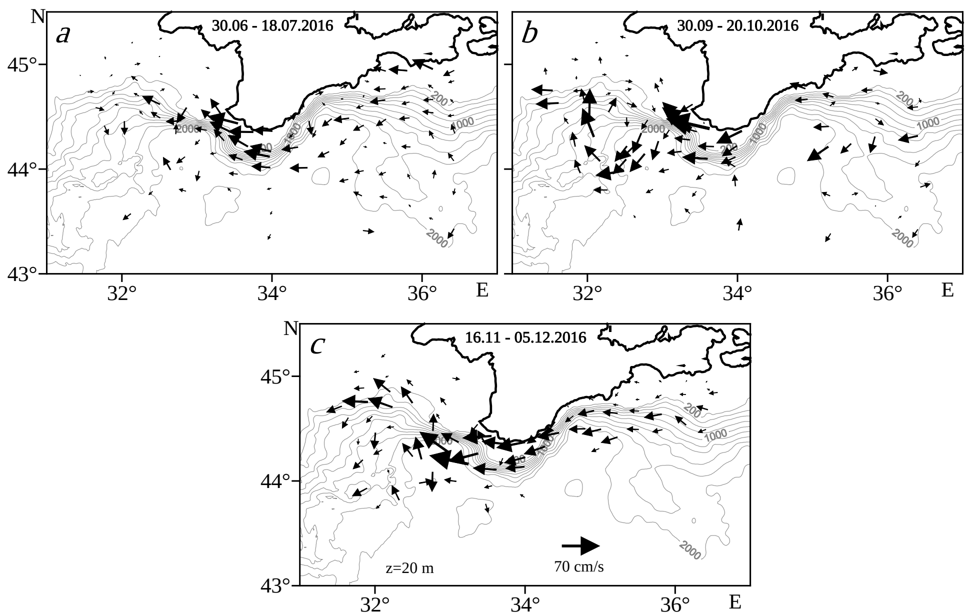
Introduction

Experimental study of vertical turbulent exchange processes is one of the crucial tasks of modern oceanology. It is determined by the need to obtain estimates of vertical flux heat, salt and nutrients, having a significant effect on the formation of the hydrological structure of water and the functioning of marine ecosystems [1]. Currently, synchronous profiles of current velocity and conditional density, measured with small-scale resolution, are widely used to estimate the parameters of vertical turbulent mixing [2–4]. This trend of experimental research was developed as a result of improved techniques for profiling currents. In particular, immersed acoustic Doppler current profilers (LADCP) make it possible to measure the current velocity profile from a vessel in the entire sensing layer [5, 6]. The existing parametrization for calculating the vertical turbulent diffusion coefficient for small-scale data [2, 7, 8] contain squares of vertical current velocity shears (hereinafter referred to as “shears”) averaged over the ensemble of profiles. The use of one or another parameterization requires an understanding of the nature of the phenomena that determine the values of shears in different layers of the sea.

The present research is aimed to represent and discuss characteristic features of the averaged vertical structure of the current velocity shears based on the analysis of the LADCP/CTD data collected in three expeditions of the R/V “Professor Vodyanitsky” in the northern Black Sea in 2016. The first expedition was held on June, 30 – July, 18 (the 87th cruise); the second one – on September, 30 – October, 20 (the 89th cruise) and the third – on November, 16 – December, 5 (the 91st cruise).

Instruments and data

LADCP based on WHM300 (300 kHz operating frequency) manufactured by RDI was used to measure currents in the expeditions. Instrument operation parameters were as follows: LADCP option is enabled in high resolution/short distance mode, time discreetness is 1 s and depth discreetness is 4 m. The measurement sequence included the instrument's exposure to the sea surface for 5 min, its further immersion at a speed of 0.5 m/s to the depth of sounding, the exposure on this horizon for 5 minutes and the subsequent rise to the surface at a speed of 0.5 m/s. Data processing was carried out taking into account the specifics of the Black Sea waters in accordance with [9]. The coordinates of the vessel were determined using GPS data, CTD measurements were carried out by the SBE911 + probe.



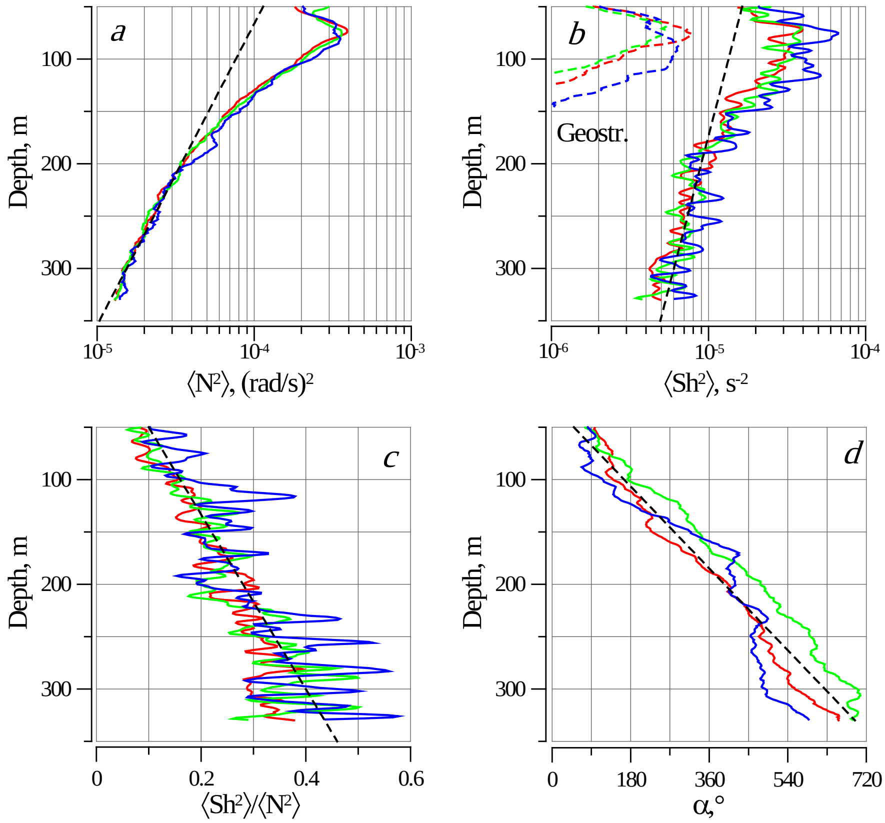
F i g. 1. Current velocities on the 20 m horizon obtained in three expeditions (the first – *a*, the second – *b*, the third – *c*)

Results of the current velocity measuring in three expeditions on the 20 m horizon are shown in vector form in Fig. 1. The measurement area was located in the northern part of the large-scale cyclonic circulation of the Black Sea waters, which is manifested in the dominance of the western direction of the measured current velocities. In the first and third expeditions a relative increase in the velocity of currents in the continental slope area is monitored. In the second expedition, in the western part of the polygon, there is a meander of the Black Sea Rim Current with a characteristic scale of ~60 km. A more detailed discussion of the horizontal structure of the current velocity is beyond the scope of the article; it is partially presented in [10].

Vertical structure of shears in the main pycnocline layer

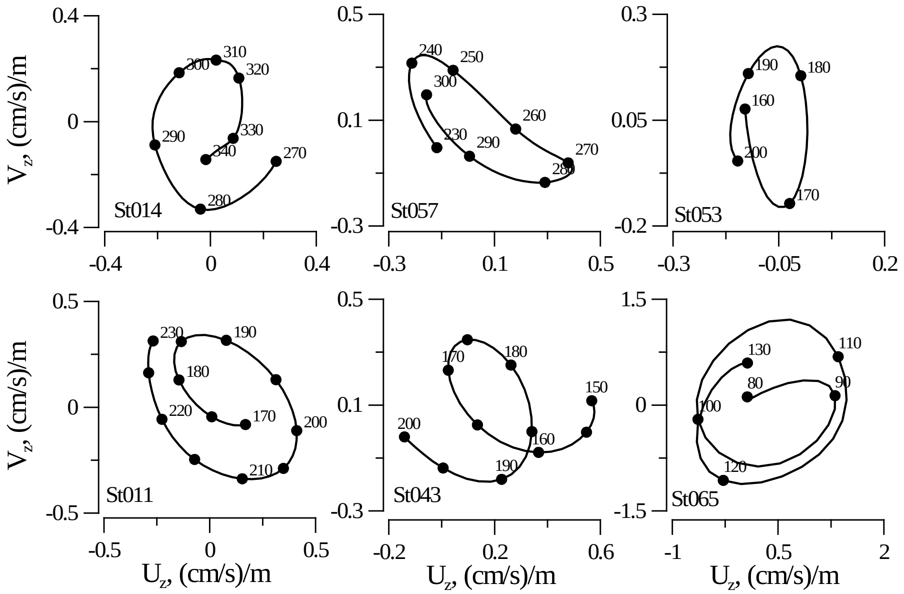
Averaging of the parameters shown in Fig. 2, was carried out on an ensemble of profiles obtained at stations at a depth of at least 1000 m in each of the three expeditions (64, 41 and 30 is the number of profiles for the first, second and third expeditions, respectively). Fig. 2, *a* shows the average profile of the square of the buoyancy frequency ($N^2 = g\rho^{-1}\rho_z$, where g is the free fall acceleration; ρ is the sea water density; ρ_z is the depth density derivative). The maximum $\langle N^2(z)\rangle$ is marked on ~75 m depth and corresponds to the average depth of isopycnal with a conditional density value of 15 kg/m^3. The black dashed line is an exponential approximating the profile in a layer of 200–300 m ($\langle N^2(z)\rangle \propto \exp(-z/125)$). Fig 2, *b* shows the mean square shear profile ($Sh^2 = U_z^2 + V_z^2$, where U_z, V_z – derivatives of the eastern U and northern V components of the current velocity). The colored dashed lines are the squares calculated from the geostrophic ratios of the shears, averaged over 10 pairs of stations of each expedition with their highest values in the vicinity of the maximum buoyancy frequency. Black dashed line is the approximating exponent ($\langle Sh^2(z)\rangle \propto \exp(-z/250)$). Black dashed lines in Fig. 2, *a*, *b* emphasize the relative increase in the mean square shear in the vicinity of the maximum buoyancy frequency. The observed increase in the mean shear value may be due to the fact that in layers with a higher buoyancy frequency the necessary condition for the linear instability of the shear flow (gradient Richardson number $Ri = N^2/Sh^2 < 0{,}25$ [11]) is carried out under the greater shear values. Deviation of the shear profile from a monotonic decrease with depth can also be explained by the contribution of geostrophic shears (Fig. 2, *b*) and the variability of currents in the frequency range less than the local inertial frequency. If the values of the shears were determined only by internal waves, then this behavior of the profile in the vicinity of the maximum buoyancy frequency would mean their intensification, which is not consistent with the data of autonomous buoy stations [12].

In tasks related to the determination of vertical mixing parameters, the ratio of the square of the shear to the square of the buoyancy frequency is ultimately important. Fig. 2, *c* gives the profile $\langle Sh^2\rangle / \langle N^2\rangle$, showing an increase in the parameter with increasing depth, which at a qualitative level ($K_V \propto \left(Sh^2/N^2\right)^2$ [8]) can be perceived as an increase in the processes of vertical turbulent mixing in the lower part of the main pycnocline.



F i g. 2. Averaged profiles of the buoyancy frequency square (*a*), square of the current velocity vertical shear (*b*), relation of the shear square to the buoyancy frequency square (*c*), turning angle of the current velocity shear vector (*d*). The first expedition – red lines, the second expedition – green lines, the third expedition – blue lines

Fig. 2, *d* shows the average profiles of the shear vector rotation angle relative to its direction on the 15 m horizon for each expedition. The middle profiles show the rotation of the shear vector clockwise with a depth of almost two turns in 50–350 m layer. This fact can be explained by the significance of the contribution of inertial oscillations to the formation of the vertical structure of the shears. Inertial oscillations are excited in the upper layer of the sea because of wind exposure [13] and propagate into the water column as internal waves with a frequency close to inertia. Such waves interact with inhomogeneities of the field of velocity of stable currents [14]. In the Northern Hemisphere, these waves, when propagating downward, are characterized by the velocity vector rotation (and, consequently, its shear) clockwise [15]. In a number of profiles, the shear rotation with depth is clearly pronounced. For an example, Fig. 3 shows the shear plots in different layers of the sea at different stations on the third expedition. In most cases, clockwise rotation is observed. Another distinctive feature of internal waves with a frequency close to the inertial one is low potential energy. An attempt to estimate the potential energy at one of the stations came down to the following.



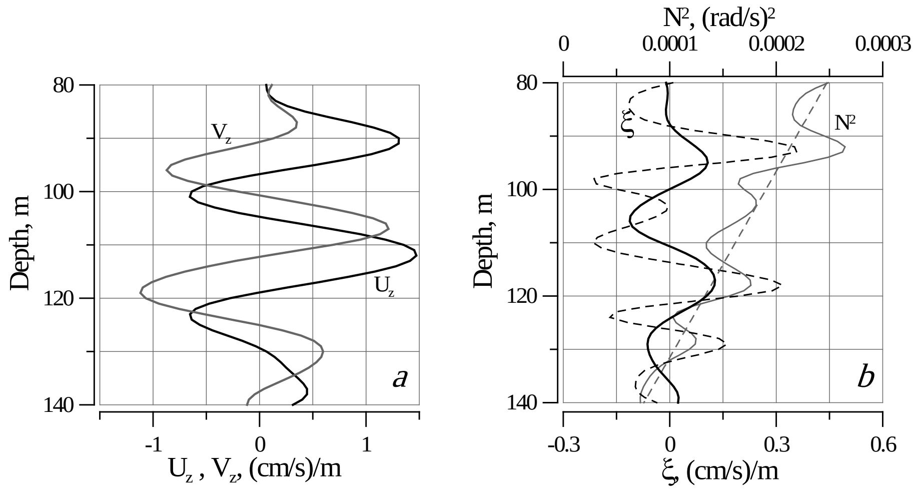
F i g. 3. Hodographs of the current velocity vertical share at different stations in the third expedition (numerical markers denote depth)

Fig. 4, *a* shows fragments of the profiles of the shear components in a layer with a well pronounced rotation of the shear vector in a clockwise direction. (Fig. 3, St065). For a single internal wave, the ratio of the kinetic and potential energies (R_ω) can be determined from the relation $R_\omega = \dfrac{Sh^2}{N^2\eta_z^2}$, where $\eta_z = \dfrac{N^2 - N_{\text{fit}}^2}{N_{\text{fit}}^2}$ is the strain (the derivative of the depth of the isopycnal displacement from the equilibrium position), N_{fit} is the buoyancy frequency in the equilibrium state [16, 17]. In Fig. 4, *b* the measured value profile N^2 is shown by a gray solid line, the linear dependence N_{fit}^2 – by the grey dashed line, the measured profile $\xi(z) = N_{fit}(z)\eta_z$ – by the black dashed line. The energy ratio was calculated as $R_\omega^{-1} = a^2 + b^2 = 0{,}0126$, where a and b were determined by the least squares method of the ratio $\xi(z) = aShU(z) + bShV(z)$ (the black solid line at Fig. 4, *b*). An estimate of the frequency of the observed wave can be obtained from the relation

$$R_\omega = \frac{(\omega^2 + f^2)(N^2 - \omega^2)}{N^2(\omega^2 - f^2)} \Rightarrow \{N >> \omega,\ \omega = (1+\delta)f,\ \delta << 1\} \Rightarrow \delta \approx \langle R_\omega \rangle^{-1} \Rightarrow \omega \approx 1{,}0126 f.$$

The result of the profile fragment analysis shows that a well-pronounced rotation of the shear vector with depth according to formal features corresponds to an near-internal wave.

A qualitative assessment of the significance of the contribution of inertial internal waves to shears in the Black Sea is consistent with data obtained at autonomous buoy stations in various regions of the World Ocean and showing the presence of a pronounced maximum of the shear spectrum in the vicinity of the local inertial frequency [18, 19].



F i g. 4. Profile fragments of the current velocity shears (*a*), and the buoyancy and deformation frequency (*b*)

Conclusion

Based on the analysis of the materials of three expeditions, the characteristic features of the averaged vertical structure of shears in the permanent pycnocline of the northern Black Sea were identified. The main feature of the average vertical shear profile is the presence of a maximum in the vicinity of the maximum buoyancy frequency. The average ratio of shears to the buoyancy frequency in a 50–350 m layer shows an almost monotonic increase with depth. On average, the clockwise rotation of the shear with depth show significant effect of near-internal waves, on the formation of the vertical structure of the shears.

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The author has read and approved the final manuscript.

The author declares that he has no conflict of interest.