

Structure of the Black Sea Currents Based on the Results of the LADCP Observations in 2004–2014

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The article presents the core results of lowered acoustic Doppler current profiler (*LADCP*) applied in the Black Sea within 2004–2014. Average features of the vertical structure of currents in the upper 600 m layer are outlined. The linear relation between vertical distribution of kinetic energy isopycnically averaged over the station ensemble and density is established. This relation is traced till the isopycn occurrence depth with density of 17 kg/m³ (~500 m). The mean current velocity has near constant value about ~ 4 cm/s in lower depth layers (>500 m), which is in a good agreement with autonomic buoys data. The averaged profile of current velocity vertical shears shows two well-separated maxima in the seasonal and main pycnocline layers. *LADCP* derived velocity shears are more than ten times exceed the geostrophic current shears. Turbulent vertical mixing coefficient, calculated by the G89 model (*Gregg* 1989) demonstrates the denominated minimum in the permanent pycnocline (4·10⁻⁶ m²/s) and increases with depth to achieve value 2·10⁻⁵ m²/s at 450 m depth. The profile of current velocity averaged by the ensemble casts in the near bottom boundary layer demonstrates near logarithmic relation.

Keywords: lowered acoustic Doppler current profiler *LADCP*, vertical structure of currents, vertical shear, vertical mixing, bottom boundary layer, Black Sea.

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Introduction

Acoustic Doppler current profilers (*ADCP*) have been actively applied in the field studies of the World Ocean dynamics for more than 30 years. These devices assist to solve a great variety of fundamental and applied problems of the modern oceanology. Profilers are produced by many manufacturers, such as *E-Teledyne RD Instruments* (USA), *SonTek* (USA), *Nortek AS* and *Aanderaa Data Instruments AS* (Norway). The 300 kHz Workhorse Monitor ADCP Profiler manufactured by *TRDI* (operating frequency – 300 kHz, nominal range – 120 m, resolution – 4 m) has been applied in the field research by Marine Hydrophysical Institute (MHI) since 2004. Overview of the device is shown in Fig. 1.

Application of *ADCP* in the *Lowered ADCP (LADCP)* mode is widespread in the study of the distribution of currents in the seas and oceans [1 – 3]. This type of measurements gives a unique opportunity to obtain the pattern of current velocity distribution throughout all the water column mass, repeatedly exceeding the operating range of the instrument [4]. The first *LADCP*-station was carried out in 1989 [5]. In subsequent years, this method has continued to be developed [6, 7]. Within the framework of the international project *WOCE LADCP* profiler became a regular oceanographic instrument [4].



Fig. 1. WHM300 overview

During measurements, the ADCP, as a rule, is mounted in the CTD probe frame. In MHI the LADCP is a separate probe consisting of WHM300 profiler, which is mounted in a frame of titanium with a battery pack (Fig. 2, left). Methodical aspects of LADCP measurements in the Black Sea and the problem of data processing issues can be found in [8 – 10].

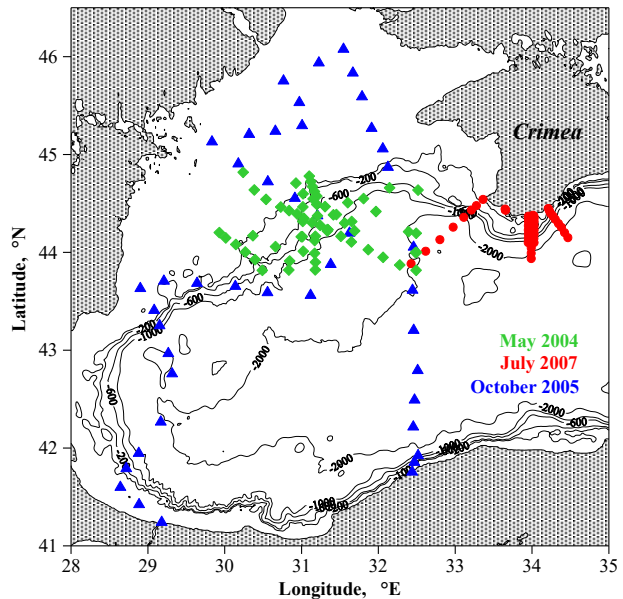


Fig. 2. Overview of LADCP (left) and station layout in three expeditions (right): Expedition 1 (green diamonds) – May, 8 – 18, 2004; Expedition 2 (blue triangles) – October, 6 – 15, 2005; Expedition 3 (red circles) – July, 18 – 22, 2007

In preparation of this article the data collected in three expeditions was mainly used. These expeditions were carried out on the stations, the location of which is schematically shown in Fig. 2, right: Expedition 1 (green diamonds) – the stations performed in R/V *Akademik* cruise by the Bulgarian Academy of Sciences on May, 9 – 18, 2004 (*GEF BSERP – RER/01/G33* project); Expedition 2 (blue triangles) – R/V *Vladimir Parshin*, October 6 – 15, 2005 *GEF BSERP – RER/01/G33* project); Expedition 3 (red circles) – in R/V *Experiment* cruise on July, 18 – 22, 2007 (MHI *Operational Oceanography* project). Total from 2004 to 2014 LADCP had been applied in 17 expeditions to different parts of the Black Sea.

Vertical Structure of Current Velocity Field

Vertical structure of current velocity field in the Black Sea is studied according to the data of instrumental observations in different ways. Dynamic method permits to obtain continuous profiles of one component of current velocity

by *CTD* profiles at two stations and has the unsolved problem to select a level of the lack of movements [11 – 12]. The autonomous buoy stations (ABS) make it possible to obtain continuous time series of measurements at fixed horizons at the point location of the station [13 – 14]. *Akvazond* [15] and *Akvalog* [16 – 18] autonomous probing profilers allow to get regular synchronous profiles of a wide range of aquatic environment parameters (including three components of current velocity) with fine-resolution for several months at the station point location. *ARGO* Floating buoys provide current velocity estimation at fixed horizons, averaged over the track on the time interval between the buoy releases to the sea surface [19, 20]. As a result of probing, *OLT* hydrophysical complex permits to obtain continuous profiles of hydrological parameters and two components of current velocity [21, 22].

Fig. 3 vectorially shows the current velocity profiles (colored arrows) and the conditional density σ_θ (gray lines) in the meridional section (31°E), crossing the anticyclonic eddy from north to south (Fig. 3, left). Data was collected in Expedition 1 (May 2004) [23, 24]. *CTD* data are supplemented by the current velocity profiles. They allow to assess the current state of water dynamics in the measurement area. In particular, according to the *LADCP* data of Expedition 1 kinematic characteristics of the anticyclonic eddy [9] and the spatial scales of the current velocity field variability in the surrounding area were determined. [24]

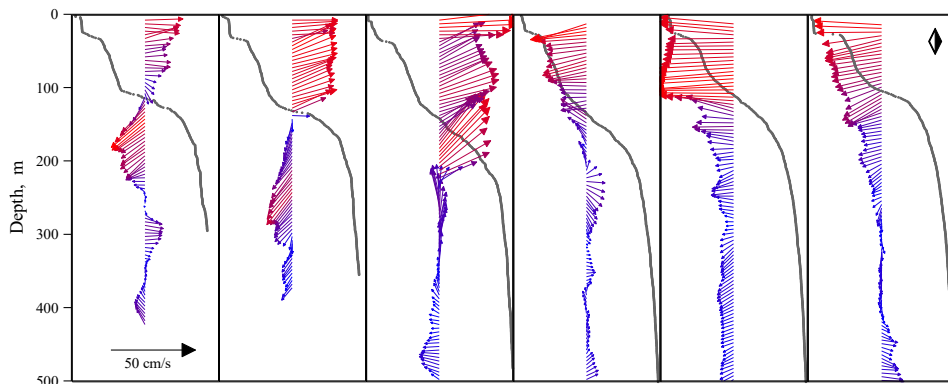


Fig. 3. Profiles of the current velocity (colored arrows) and the density (gray lines) in the meridional section, May, 2004

In the continental slope area a pronounced correlation of the vertical current velocity field structure with the vertical distribution of the conditional density is observed. Fig. 4, left, shows a graph of the dependence of the kinetic energy of the currents (red line) ($E_K = (U^2 + V^2)/2$) from the conditional density, isopycnally averaged over the ensemble of the stations in Expedition 1 ($EK = \langle E_K(\sigma_\theta) \rangle$, where $\langle \dots \rangle$ is an averaging operator); blue line marks the graph of available potential

energy $EP = \langle 0,5\xi^2 N^2 \rangle$ (where ξ is an isopycnal displacement from the middle position); green line indicates the frequency graph of buoyancy $\left(N = \sqrt{\frac{g}{\rho} \frac{\partial \sigma_\theta}{\partial z}} \right)$.

Fig. 4, right, shows the isopycnally averaged kinetic profiles (red line) and the available potential (blue line) energy, as well as the conditional density (green line). There is an almost linear dependence of the kinetic energy distribution of the conditional density (black dotted line) $\langle EK(\sigma_\theta) \rangle = 0,277 - 0,0164\sigma_\theta$ (Fig. 4, left) in the upper layer of 20 – 240 m (density of 13.6 – 16.6 kg/m³). In the lower layers the kinetic energy decreases more slowly, and at a depth of ~400 m ($\sigma_\theta = 16,9$ kg/m³), its value goes to an almost stationary level.

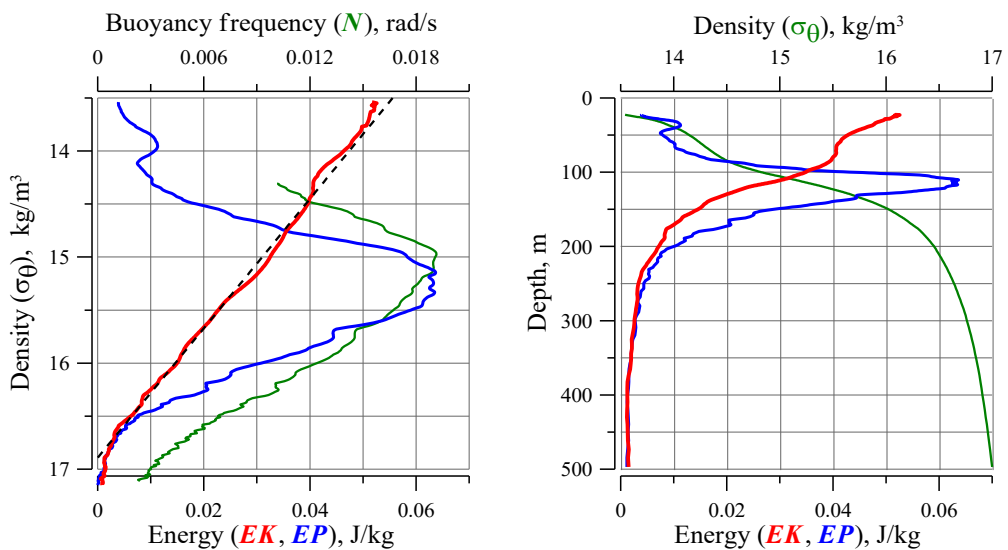


Fig. 4. Dependence of the kinetic (red line) and the available potential energy (blue line) from the conditional density (left) and depth (right). Green line indicates the buoyancy frequency (left) and the conditional density (right); black dotted line – the dependence of the kinetic energy distribution of the conditional density

Fig. 5 shows the mean current velocity profiles module ($|U| = \sqrt{2EK}$) obtained according to the data of *LADCP* in 2004 (red line) and autonomous buoy stations in 1955 – 1983 (blue line) [25]. Green solid line indicates the profile of the mean conditional density, dotted lines – profiles at the separate stations.

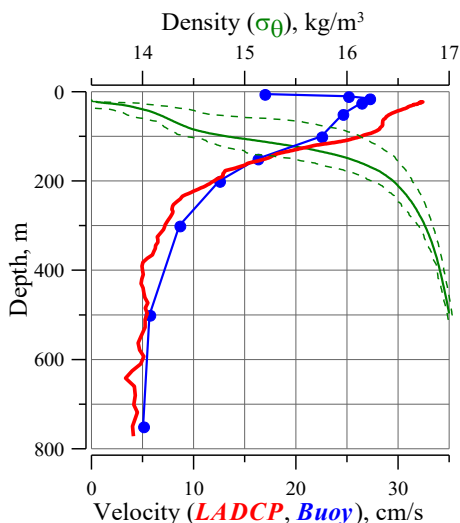


Fig. 5. Mean profiles of the current velocity according to the data *LADCP* in May, 2004 (red line) and buoy stations in 1955 – 1983 (blue line); the conditional density in May, 2004 (green line); profiles on the separate stations (dotted lines)

The trends typical for the World Ocean dynamics are manifested in the vertical distribution of current velocity in the Black Sea. For example, the North Atlantic is characterized by a significant component of barotropic currents penetrating to greater depths and reaching an amount of 10 cm/s [26 – 28]. At that, the baroclinic inhomogeneity of the current velocity field is concentrated in the upper 1000 m layer [26]. In the Black Sea the layer of baroclinic/shear currents, according to the *LADCP* observations is limited by the upper 300 – 500 m layer, or depth of occurrence of isopycnal of $\sigma_{\theta} = 16,9 \text{ kg/m}^3$.

In the lower layers sea (750 – 1700 m) the barotropic component of current velocity, according to *ARGO* floating buoys, is 2 – 3 cm/s [19 – 20]. A similar estimation of the current velocity in the lower sea layer obtained based on the *Akvalog* profiler data [18].

Vertical shears of currents

Interest to the study of vertical shears of currents is mainly supported by the fact that the shear instability is represented by the principal mechanism of vertical mixing in the seas and oceans [29]. A large number of models/parametrizations connects the turbulent mixing with the Richardson number $\left(Ri = \frac{N^2}{Sh^2} \right)$. *PP81* parameterization [30] is widely applied in numerical simulation. It is similar to previously published summarized dependencies. In the Black Sea, in the words of the authors of the article [22, p. 14], "the main feature of the vertical structure of the currents is sharply-layered structure of the velocity field, at that, the layer boundaries coincide with the boundaries of the thermohaline structures and are located at depths of change of vertical density gradients. The maximum vertical shifts are registered near the core of the cold intermediate layer (CIL), where there is a break in the density gradient. "

Maximal velocity shears, according to [14], are located in layers of 10 – 25 m and 50 – 300 m. The authors of the paper [24] showed that in the Black Sea, the mean profile of the vertical shears has two well-defined maxima in the layers of the seasonal thermocline/pycnocline and main halocline/pycnocline. Maximal vertical shear in the density contrast layer separating the Azov and Black Sea waters is observed in the southern part of the Kerch Strait [31].

Fig. 6 (left) shows the profiles of the latitudinal (U) and meridional (V) current velocity and conditional density components obtained at one of the stations in 2004, where the depth resolution of the *ADCP* measurements was set to 2 m. In the seasonal thermocline layer, the maximum value of the buoyancy frequency reached 0.044 rad/s, the vertical shear of currents was 0.064 s^{-1} . The corresponding Richardson number was 0.47, which exceeded its critical value of 0.25 [32]. Above the seasonal thermocline, at a depth of less than 10 m from the sea surface, the Ri values become less critical. This phenomenon was also observed in the coastal shelf waters of the Black Sea [15] and in the upper layer of the southern part of the Kerch Strait [33]. The maximum vertical shear of currents in the seasonal thermocline layer is quite often observed. Fig. 6 (right) demonstrates the mean profiles of vertical current shear (red line) and buoyancy frequency (green line). Averaging was performed relative to the depth of occurrence of the seasonal thermocline center. The Ri value at a depth of 15 m is ~ 1 , in the seasonal thermocline – ~ 7 and below 35 m – ~ 9 .

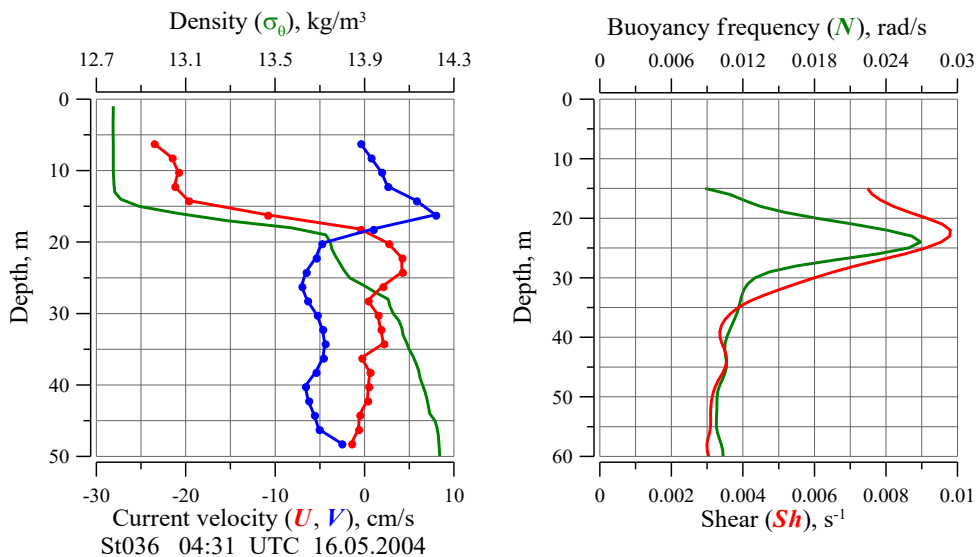


Fig. 6. Left – the profiles of the latitudinal (U) and meridional (V) current velocity and conditional density components obtained at one of the stations in 2004. Right – the mean profiles of vertical current shear (red line) and buoyancy frequency (green line), averaged over the station ensemble

Fig. 7 (left) presents an example of the profiles of the components of the relative current velocity (reference horizon is 240 m) and the conditional density obtained at one of the stations in 2012 in the main pycnocline layer. The observed distribution of currents can be explained by the passage of an internal wave (IW) through the main halocline layer. Vertical length of the IW is 50 – 60 m, the amplitude is about 12 cm/s. The rotation of the current velocity vector with depth goes clockwise. For the northern hemisphere it means the downward propagation of the IW [34]. Intensive IW in the main halocline layer, according to *LADCP* measurements, was observed predominantly in the area of the continental slope during autumn, winter and spring.

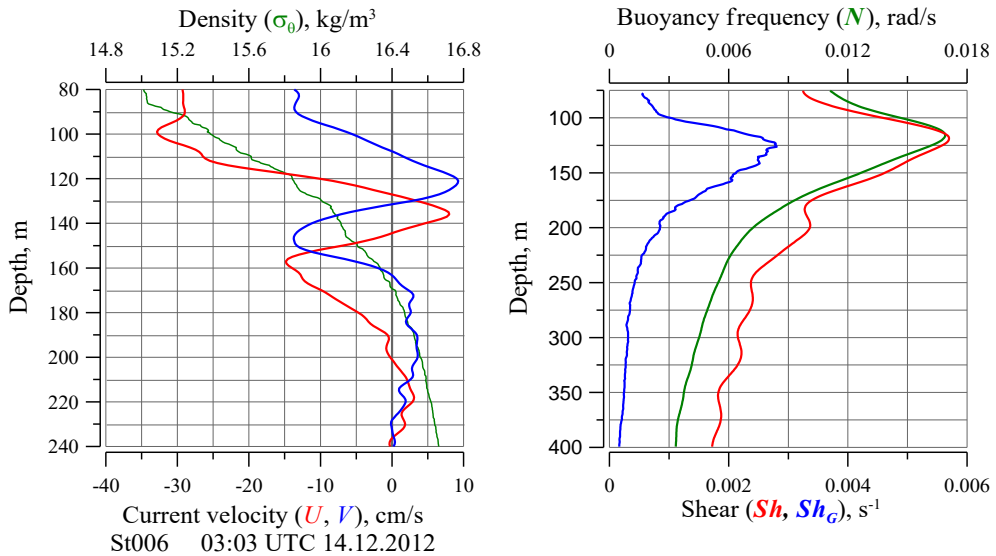


Fig. 7. Left – the profiles of the latitudinal (red line) and meridional (blue line) current velocity and conditional density components (green line) obtained at the separate station. Right – the mean profiles of the buoyancy frequency (green line), the geostrophic (blue line) and the measured (red line) current velocity shears

Fig. 7 (right) shows the mean profiles of the buoyancy frequency (green line), the geostrophic (blue line) and the measured (red line) current velocity shears. The maximum of vertical shears is observed in the main pycnocline layer. For vertical shears of geostrophic currents, Ri is ~ 30 in the main pycnocline layer, then it increases with depth, reaching a value of ~ 300 at the horizon of 400 m. According to the LADCP measured shears in the main pycnocline layer, Ri is ~ 10 , in the lower layers the Richardson number decreases to ~ 4 at a depth of 400 m.

The significant difference between the profiles of geostrophic and measured shears is explained by the fact that the value of shears in the lower layers of the Black Sea is mainly determined by ageostrophic processes, such as, for example, internal waves (see Fig. 7, left). When substituting the obtained profiles of geostrophic and measured shears in the *PP81* parameterization, a decrease with depth of the vertical turbulent mixing coefficient will be observed in the first case and in the second case – there will be an increase.

Vertical mixing

Vertical turbulent mixing in the seas and oceans has been remained one of the most interesting issues of applied oceanology for a long time. In recent decades, microstructured data collected using free-fall probes are used for the diapycnic exchange estimation. This data is considered to be the most reliable [2, 35 – 38]. Additionally, data of small-scale *CTD/ADCP* measurements [1, 2, 15, 36, 39 – 41] are also widely used.

Basis of the most models connecting small-scale characteristics of hydrophysical fields with vertical mixing parameters is the assumption that in a statically stationary field of internal waves turbulent kinetic energy is produced at

the velocity equal to the velocity of its transmission along the IW spectrum in the direction of decrease of vertical scales due to the interaction between waves [42]. One of these models, the G89 model [43], is often used to estimate the turbulent kinetic energy dissipation velocity [2, 36 and 40]:

$$\varepsilon = 7 \cdot 10^{-10} \frac{N^2 \langle Sh^4 \rangle_{10}}{N_o^2 \langle Sh_{GM76}^4 \rangle}, \quad (1)$$

where ε is the turbulent kinetic energy dissipation velocity, W/kg; $N = \sqrt{\frac{g}{\rho} \frac{\partial \sigma_\theta}{\partial z}}$ is the buoyancy frequency; Sh is the vertical shear of current velocity (further – the shear), $Sh = \sqrt{(\Delta U / \Delta z)^2 + (\Delta V / \Delta z)^2}$, $\langle Sh^4 \rangle_{10}$ is the mean value of the fourth degree of shear determined at 10-meter intervals; $\langle Sh_{GM76}^4 \rangle$ is the mean value of the fourth power of the shear, obtained by integrating the spectrum of internal waves GM76 [44, 45]; $N_o = 5.24 \cdot 10^{-3}$ rad/s is the buoyancy frequency of GM76. The vertical diffusion coefficient K_p is determined from the following relation [46]

$$K_p = \Gamma \frac{\varepsilon}{N^2}, \quad (2)$$

where K_p is the vertical diffusion coefficient, m²/s; Γ is The the mixing efficiency coefficient, usually taken as equal to 0.2 [47].

In the Black Sea, the profiles of shears and buoyancy frequencies have a well-pronounced maximum in the main halocline/pycnocline layer [22, 24]. Fig. 8 shows the profiles of the square of the current velocity shear (gray circles, red line) and the square of the buoyancy frequency (gray crosses, green line) averaged over the ensemble of 26 stations of the Expedition 1. The averaging was carried out with respect to the depth of occurrence of the pycnocline center with the subsequent shear of the resulting profile to the value average over the ensemble of stations. Shears and buoyancy frequency were determined at 10-meter intervals.

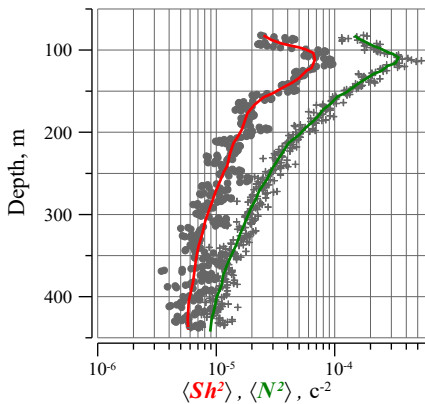


Fig. 8. Mean profiles of the square of the current velocity shear (gray circles, red line) and the square of the buoyancy frequency (gray crosses, green line)

Fig. 9 (left) demonstrates the average profiles of the velocity of the kinetic turbulent energy dissipation (gray circles mark the initial data, red line – after low-frequency filtration), calculated from the relation (1). The present dependency graph shows the presence of a well-pronounced maximum in the main pycnocline layer, where ε reaches $6 \cdot 10^{-9}$ W/kg, in layers below 200 m ε decreases with depth and at a horizon of 400 m its value is $9 \cdot 10^{-10}$ W/kg.

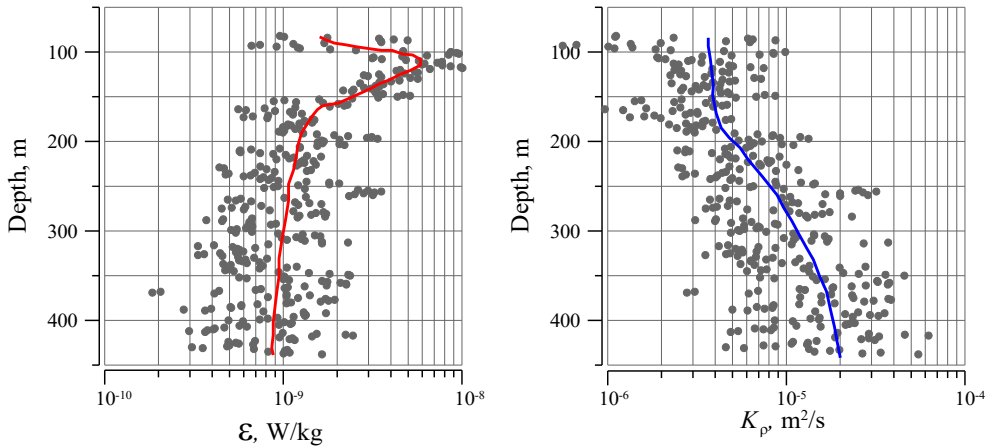


Fig. 9. Left – the average profile of the velocity of the kinetic turbulent energy dissipation (gray circles mark the initial data, red line – after low-frequency filtration). Right – the profile of the vertical turbulent diffusion coefficient (gray circles are the initial data, the blue line – the data after filtration)

Fig. 9 (right) shows the profile of the vertical turbulent diffusion coefficient (gray circles are the initial data, the blue line – the data after filtration) calculated according to the relation (2). In the main pycnocline layer K_p takes the minimum values of $4 \cdot 10^{-6} \text{ m}^2/\text{s}$, in layers below 200 m it increases with depth and at the horizon of 300 m reaches a value of $10^{-5} \text{ m}^2/\text{s}$. The obtained estimates of the vertical mixing coefficient turned out to be somewhat smaller than in the previously published works by

S.G. Boguslavsky & I.K. Ivashchenko [48] – $K_p = (3.1 \div 4.4) \cdot 10^{-4} \text{ m}^2/\text{s}$ at a depth of 500 m;

V.N. Eremeev & V.M. Kushnir [22] – $K_p = (3 \div 5) \cdot 10^{-5} \text{ m}^2/\text{s}$ in the main halocline;

A.S. Samodurov & A.M. Chukharev [49] – $K_p = (2 \div 8) \cdot 10^{-5} \text{ m}^2/\text{s}$ in the main pycnocline;

A.G. Zatsepin & co-authors [38] – $K_p = 4 \cdot 10^{-6} \div 5 \cdot 10^{-5} \text{ m}^2/\text{s}$ in the layer below the seasonal thermocline to 170 m for summer and autumn.

The values of the vertical mixing coefficient for summer, given in [38], are in good agreement with the estimates obtained according to the data of *CTD/LADCP* observations.

A considerable dispersion in the estimates of the turbulent diffusion coefficient can be due to both the spatiotemporal variability of vertical mixing processes and the difference in the estimation methods. Taking into consideration the wide application of *LADCP* together with *CTD*, the approach can be used to study vertical mixing processes, especially in deep sea layers, where microstructural data is difficult to obtain.

Near-bottom boundary layer

Experimental study of the parameters of the near-bottom boundary layer in the seas and oceans is one of the topical problems of applied oceanography. The results of such studies can be useful for regulating the parameters of numerical models of water circulation and dynamic processes in the sea, in solving problems of soil erosion, sedimentation, etc. Empirical dependences of the near-bottom boundary layer parameters for mean ocean conditions are presently known [50]. In the Black Sea, the empirical characteristics of the near-bottom boundary layer were previously obtained using *OLT* – a modified hydrological probing complex [51, 52].

In July 2007 and 2009, the specific measurements were carried out in the area of the Black Sea experimental sub-satellite polygon. They were aimed to study dynamics of the near-bottom boundary layer. Fig. 10 schematically shows the location of stations in the expeditions during July 20 – 21, 2007 (squares) and July 29 – 30, 2009 (triangles). *ADCP WHM300* was applied as a measuring instrument of current velocity profiles. The discreteness of the measurements over depth was set at 4 m, over time – 1 second, the bottom tracking option was enabled. To obtain current profiles in the near-bottom area, a 10-minute exposure of the instrument was carried out at a distance of 60 to 80 m from the bottom.

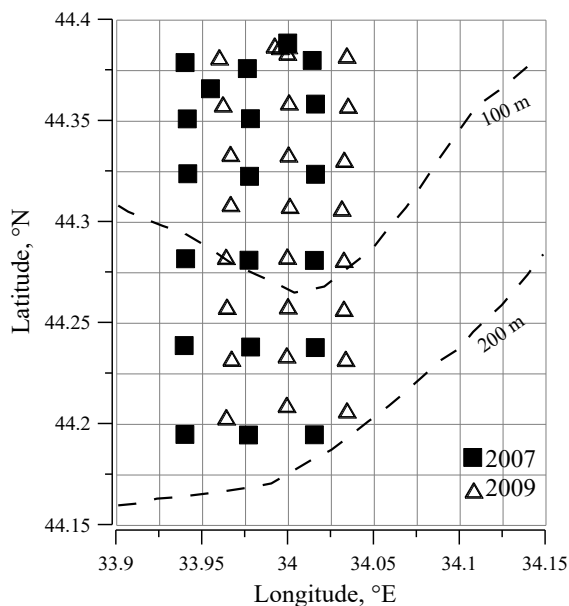


Fig. 10. Location map of the stations: July 20 – 21, 2007 (squares) and July 29 – 30, 2009 (triangles)

The results of the measurements showed that in a particular profile of the current velocity, the pronounced patterns of behavior in the near-bottom area are not revealed. This is largely due to the fact that the instrument registers the entire set of dynamic processes, including internal waves, inertial oscillations, etc. [53].

Fig. 11 presents an example of the profiles of the velocity and density components in the near-bottom layer, presumably during the passage (generation and reflection) of the internal wave.

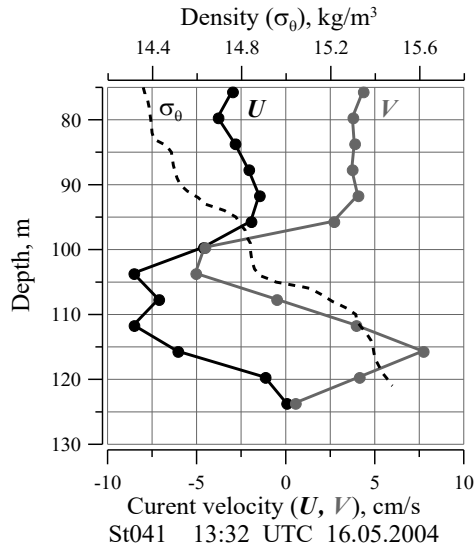


Fig. 11. Profiles of the velocity and density components in the near-bottom layer during the passage of the internal wave

In Fig. 12 the black continuous lines mark the current velocity profiles averaged over the ensemble of stations, depending on the distance to the bottom for the expeditions in 2007 and 2009. The direct dotted line is the empirical dependence of the current velocity at the upper boundary of the near-bottom boundary layer [52]. The average velocity profiles of currents can be adequately approximated by the following logarithmic dependences [29]:

$$U = \frac{u_*}{k} \ln \left(\frac{z}{z_b} \right), \quad (3)$$

where u_* is the friction velocity; k is Kármán's constant (0,41); z_b is the height of bottom surface roughness; z is the distance to the bottom. The corresponding approximating functions are indicated by gray dotted lines in Fig. 12. The friction velocity was 3.14 cm/s and 2.46 cm/s for 2007 and 2009 respectively. The bottom roughness is the same for the two expeditions and is equal to 0.4 m. The value of the bottom friction coefficient is calculated according to the following ratio

$$C_b = \left(\frac{u_*}{U} \right)^2, \quad (4)$$

where U is the velocity of current in the upper boundary of the near-bottom boundary layer, that equals ~ 0.007 , being more than 4 times higher than given in [51]. The friction velocity estimation, is calculated according to the following ratio [50]

$$u_* = 2.5 \cdot H \cdot f, \quad (5)$$

where H is the boundary layer thickness [52]; f is the Coriolis parameter that equals 1.5 cm/s for 2007 and 1.14 cm/s for 2009, which is two times less than the values obtained on the basis of *ADCP*-measurements. The observed discrepancy between near-bottom boundary layer parameter estimations can be explained both by the difference in the methods of instrumental estimation and by the increased dynamic activity in the area of the Black Sea experimental sub-satellite polygon [54].

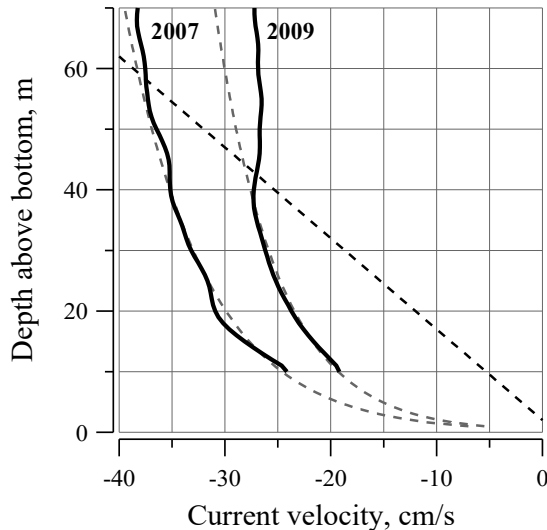


Fig. 12. The mean current velocity profiles in the near-bottom layer (black continuous lines); the empirical dependence of the current velocity at the upper boundary of the near-bottom boundary layer (direct dotted line)

Conclusion

A limited amount of the field material for brief summary of the ten-year *LADCP* experience is presented within the framework of this article. The results of the profiler application in the expeditionary practice of Marine Hydrophysical Institute broadened the concept of the vertical structure of the currents in the Black Sea. In particular, the characteristics of small-scale processes both in the water column and in the boundary layers were studied in greater detail. Summarizing, it may be concluded that the acoustic Doppler current profilers are undoubtedly the most powerful tool for studying the water dynamics and its variability over a wide range of spatio-temporal scales.

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