ISSN 1573-160X, *PHYSICAL OCEANOGRAPHY*, Vol. 30, Iss. 6, pp. 689-713 (2023)
Original Russian Text © The Authors, 2023,
published in *Morskoy Gidrofizicheskiy Zhurnal*, 2023, Vol. 39, Iss. 6, pp. 735–759

Original article

Vertical Turbulent Exchange in the Black Sea: Experimental Studies and Modeling

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Abstract
Purpose. The paper is purposed at summarizing the main results of experimental and theoretical studies of vertical turbulent exchange in the upper mixed layer and stratified layers of the Black Sea carried out in recent years.
Methods and Results. The equations for semi-empirical dependences of turbulence intensity on the governing parameters are proposed, based on a large amount of experimental data on the turbulent structure obtained on the research vessels and a stationary oceanographic platform using modern high-frequency equipment combined with conventional measurements of main hydrophysical characteristics. The experimental data obtained were used to verify theoretical models and to specify empirical coefficients in the proposed equations. A multiscale model was applied additionally to the Kraus – Turner model to forecast reliably the upper mixed layer deepening after a storm. The turbulent energy dissipation rate and the turbulent diffusion coefficient in the stratified layers were found using the data on microstructure of hydrophysical fields. The coefficient dependences on buoyancy frequency in different layers are expressed by a power function with different degree indices.
Conclusions. Having been examined in detail, the stratification conditions as well as a large array of sounding data made it possible to identify five layers with different density gradients and different mechanisms dominant in generating turbulence. Such a differentiation specifies the expressions describing turbulent diffusion intensity depending on the layer depth and physical and geographical conditions affecting vertical exchange. On the whole, the resulting power-law dependences agree well with the earlier developed 1.5D model of vertical turbulent exchange for the Black Sea. The proposed way of considering the effect of turbulence generation mechanisms in the upper mixed layer improves correspondence between the model calculations and the experimental data. The Kraus – Turner model supplemented with the multiscale turbulence model permits to forecast deepening of the mixed layer resulting from storm conditions.

Keywords: Black Sea, turbulent exchange, upper mixed layer, stratified layers, dissipation rate, turbulent diffusion coefficient, modeling, experimental data

Acknowledgements: Within the framework of state assignment of FSBSI FRC MHI, theme FNNN-2021-0004 "Oceanological processes", the experimental studies, data processing and partial analysis, modernization of a multiscale model for the sea surface layer, and specification of functional dependencies of the turbulent diffusion coefficient in stratified layers were implemented. Modeling and analysis of the UML thickness dynamics in the experiments, records analysis and parameterization of the Langmuir circulation were performed with the financial support of the RSF grant 22-17-00150.

For citation: Samodurov, A.S., Chukharev, A.M., Kazakov, D.A., Pavlov, M.I. and Korzhuev, V.A., 2023. Vertical Turbulent Exchange in the Black Sea: Experimental Studies and Modeling. *Physical Oceanography*, 30(6), pp. 689-713.

1. Introduction

Vertical turbulent exchange plays a significant role in all oceanographic processes: physical, chemical, biological and largely determines the ability of the sea to self-purify and transport natural and anthropogenic impurities. The vertical distribution of temperature, salinity, nutrients and oxygen depends on the turbulent mixing intensity and its spatial and temporal variability. Sea surface processes, relationship between surface and gravity waves, wind and currents in adjacent boundary layers are the most important factors in the global climate system [1].

A fundamentally important factor affecting the development and intensity of vertical exchange in the ocean is density stratification. The mechanisms of turbulence generation in the upper mixed layer and in stratified layers differ significantly; as a rule, they are studied by different methods and, accordingly, different modeling approaches are used.

To adequately describe physical and other processes in the upper mixed layer of the sea, the most accurate understanding of the complex interactions between current, surface waves, turbulence and appropriate parameterization is required. The most common method for this is application of semi-empirical relations, which make it possible to estimate the fluxes of momentum, energy and matter using exchange coefficients and gradients of the corresponding quantities. However, a variety of hydrometeorological situations, a great variability of these coefficients and a lack of reliable relationships for their calculation do not always offer a possibility to obtain a satisfactory agreement between calculated and measured values.

Various researchers considered both surface waves [2, 3] and drift current velocity shear [4] to be the dominant mechanisms for generating turbulence. Subsequently, breaking waves were assumed to be the main source of turbulence [5] and drift current velocity shear was taken into account as a secondary source. A multiscale model [6] considers all three generation mechanisms listed above, but in a number of cases it also does not provide a good agreement with experimental results. A possible cause for the discrepancy between model calculations and measurements is, in particular, the absence of such turbulence sources as Langmuir circulations (LC) and microbreaking in the model.

In [7], a boundary condition with wave parameterization depending on wind stress was developed. In [8], L. Kantha and K. Clayson revised the turbulence closure model to include Langmuir effects by adding Stokes drift to the turbulent energy balance equation. Their results showed that wave breaking affected the mixed layer properties in the top few meters, while Langmuir cells contributed to the mixed layer deepening. In [9–11] and others, various aspects of wave breaking were considered; experimental estimates of the parameters characterizing the wave energy loss and the transformation of this energy into turbulence were made.

The main source of maintaining energy dissipation and vertical turbulent diffusion in the main water column of a stably stratified ocean, away from sharp frontal zones, areas of pronounced manifestation of double diffusion mechanisms, etc., is the mechanism of shear instability in the field of quasi-inertial internal waves (IW) [12]. Many publications were devoted to assessing the contribution of this mechanism to vertical exchange. The main direction of these studies is related to the search for power-law dependences of the energy dissipation rate ε and the vertical turbulent diffusion coefficient associated with it through the Osborn relation [13] on the buoyancy frequency N. Knowing the buoyancy frequency distribution over the depth from hydrological observations, it is easy to obtain the dependence of the diffusion coefficient on depth.

To identify the desired theoretical dependencies, various approaches are applied. For example, in [14–16] the IW analytical and numerical models that take into account the mechanisms of nonlinear energy transfer to waves of low frequencies and small vertical scales are used. As a result, the authors obtained a quadratic function of energy dissipation rate on buoyancy frequency. In other papers [17, 18], various power-law dependences of ε on N were obtained, where the exponent was from 1 to 2. Note that each of these models offers a single power-law dependence for the entire stratified layer, which, in our opinion, does not reflect the real picture of vertical exchange processes.

Contemporary data on fine structure [19] demonstrate that in the deep ocean layers (at up to 5300 m depths with a dissipation rate of approximately 10^{-10} $m^2{\cdot}s^{-3}$) turbulence is generated due to short-period (< 0.5 h) rather intense overturning cells with a vertical scale of less than 5 m. Since the inertial sub-range of turbulence is found to extend into the inner wave band, overturning occurs predominantly as a result of a current velocity shear associated with inertial frequencies.

In previous works carried out in Turbulence Department in recent years [20, 21], an ocean IW climatic spectrum model was constructed, which adequately describes the observed structure of one-dimensional spectra in the ocean pycnocline. Moreover, a model for determining the dependence of turbulent energy dissipation rate and turbulent diffusion coefficient on the local buoyancy frequency was developed to take into account the contribution of quasi-inertial IW shear instability to mixing. In this model, the region under consideration is divided into two parts: the upper stratified layer and the main pycnocline. It is shown that the structure of dependence of vertical turbulent diffusion coefficient on stratification should be different for each of the layers under consideration.

In [20], the main attention is paid to the role of instability and breaking of inertial-gravity IW in the transition zone separating the shelf and continental slope as a factor in intensification of mixing and vertical exchange in the upper stratified layer of the Black Sea. Subsequently, based on a 1.5D (one and a half-dimensional) model, five layers with different vertical exchange coefficients depending on stratification were identified in the general stratified depth of the Black Sea [21] for the first time. This improved approach to describing the turbulent structure in the stratified sea column offers a possibility to clarify vertical exchange features in different layers and take into account the effect of dynamic factors and bottom topography.

Based on the experimental data, we obtained a number of results in our papers that provided a clearer picture of the dependence of turbulent exchange intensity on environmental conditions and physical processes affecting vertical mixing in the mixed and stratified layers of the Black Sea. It was the goal of this paper to present a generalized picture of practical methods for estimating exchange coefficients.

2. Turbulent exchange in the upper mixed layer of the sea

2.1. Development of a multiscale turbulence model

Turbulence near the sea surface has been studied by the Turbulence Department members for quite a long time, both experimentally and theoretically. In particular, the developed physical and mathematical multiscale model of turbulent exchange in the near-surface layer corresponds to the experimental data [6, 22] quite well. However, the situations where none of the considered models, including multiscale ones, provide good results are often observed. A possible cause for this is incomplete consideration of the existing mechanisms of turbulence generation, in particular, Langmuir circulations (LC) [3].

The technique for LC experimental study was developed based on the works [23–25]. To record downward and upward flows in the convergence and divergence zones that arise in coherent Langmuir structures, DVS6000 acoustic meter (Fig. 1, *a*), located just above the middle of the mixed layer, is used. Vostok-M meter is located at the same horizon (Fig. 1, *b*) to record average values of current velocity, electrical conductivity and temperature. The positional version of Sigma-1 measuring complex (Fig. 1, *c*) is applied to assess the turbulent processes intensity. The process of LC experimental study was as follows: at a steady wind velocity of 7–17 m/s, markers in the form of sheets of thick paper measuring ~ 10 × 15 cm were thrown onto the sea surface, which, in the presence of LC, lined up in clearly visible bands. The formation of bands, their width, the distance between bands visible from markers, algae or sea foam are assessed visually; during the experiment, photo and video recording of the surface state is carried out. Sigma-1 complex is placed sequentially at horizons from 1 to 7 m to record fluctuation characteristics and it is being held for 15–20 min at each horizon.

The observations were accompanied by recording of background hydrometeorological parameters: wind velocity and direction, temperature, wave characteristics.

a *b* *c*

F i g. 1. Set of devices for studying turbulence in the sea near-surface layer: DVS6000 (*a*), Vostok-M (*b*) and Sigma-1 (*c*)

Based on visual observations of Langmuir bands on the surface, it was found:

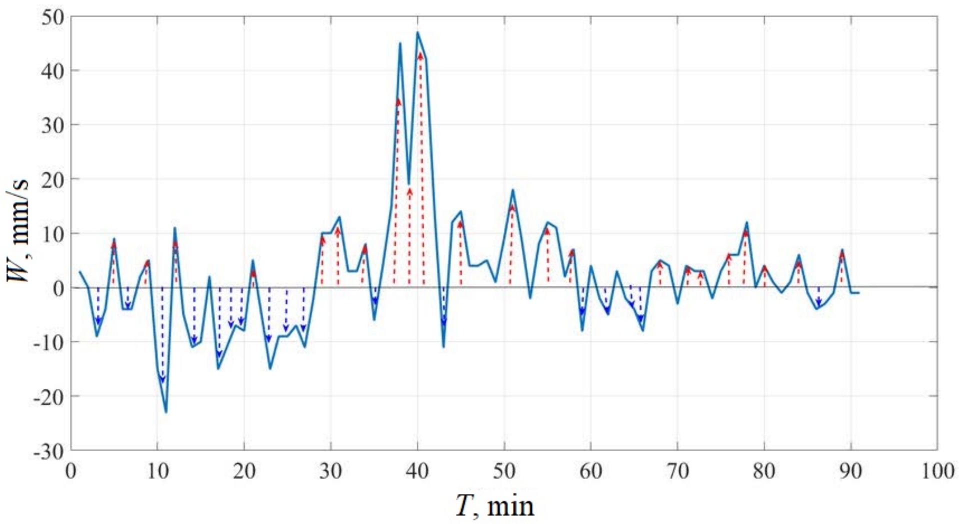
– at wind velocities of up to 4 m/s, the bands are rather weakly expressed;

– bands become clearly visible at wind velocities of more than 6 m/s;

– with a steady wind velocity of 9–13 m/s, stable, clearly defined bands appear;

– at wind velocities of 16–20 m/s, the bands are destroyed quite quickly, since with a sharp wind direction change the bands do not have time to "reform", they are unstable and quickly mix.

Based on the continuous data obtained by DVS6000 current velocity meter over several days, convergence and divergence zones were identified. Since the LC structures gradually displace to the right of the wind direction, in the measurement zone we consistently see alternation of these zones. An example of a recording is shown in Fig. 2 (measurements at 2.5 m horizon). It should be noted that strict regularity in the alternation of zones in our recordings is not always found. The vertical direction of the flow velocity in the convergence and divergence zones is indicated in the images by red and blue arrows. In our data, as in the measurement data of many other authors, the velocities are higher in the convergence zones (amplitude W in Fig. 2), but the width of the bands is smaller than in the divergence zones. In the convergence zones, an almost doubling of horizontal flow velocity, which was also observed by many other authors, was found. The maximum rate of displacement of structures to the right of the wind direction V_{displ} = 0.014 m/s was recorded at the highest wind velocity V_{10} = 11.8 m/s, when a stable LC system was still preserved.



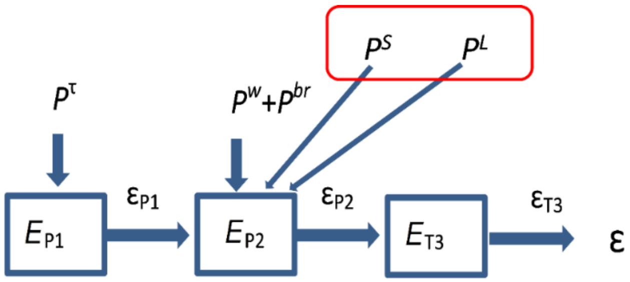
F i g. 2. Convergence and divergence zones on the record of vertical velocity component at 2.5 m horizon during 90 min. Red and blue arrows indicate local velocity maxima in the upward and downward flows

In our opinion, different amplitudes of vertical velocities and the absence of a clear periodicity of the convergence and divergence zones in the records are explained by a complex system of LC: two or more smaller scale structures can be located inside a larger Langmuir cell.

Analysis of DVS6000 synchronous recordings of vertical velocities and vertical velocity fluctuations recorded by Sigma complex revealed fairly clear peaks in the coefficient of positive and negative cross-correlation. In general, however, the correlation level of the analyzed values turned out to be low that can be explained by the remoteness of the instruments from each other.

It was not possible to identify a statistically significant correlation between turbulence intensity (dissipation rate of turbulent energy ε) and the LC characteristics at this stage. However, a regime was found, where the LC increase the intensity of turbulent mixing in the surface layer. These are changes in wind direction by an angle Δα within the range of 10–20°, which, in our opinion, leads to the LC restructuring and an increase in the instability of fluid movements. A deeper study of the issue is required to parameterize this process and ultimately develop a predictive model. The tested methodology for the LC recording and taking into account their effect on turbulent mixing has shown sufficient efficiency; however, some important characteristics cannot be determined from such measurements, in particular, the spatial structure of LC including their direction. Perhaps, more careful experimental verification of the calculation of lateral displacement rate of structures is also required.

As already mentioned, experimental observations of the LC were carried out to parameterize them and include this mechanism in physical and mathematical models of turbulent mixing. The most promising in this regard seems to be a multiscale turbulence model, which already considers all the main mechanisms of turbulence generation in the surface layer [6]. Its new improved version adds the ability to take into account the effect of Stokes drift and LC.



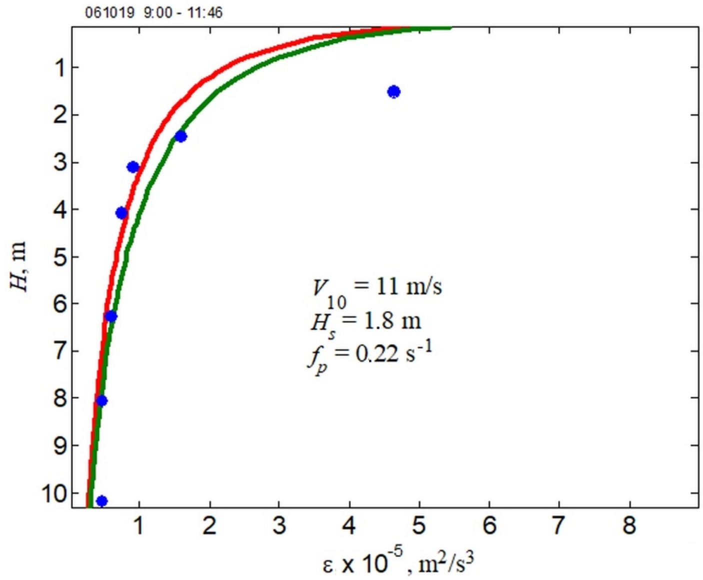
F i g. 3. Scheme of calculating turbulent energy generation, its transfer along the spectrum and dissipation in the multiscale model [6]

The energy spectrum in the multiscale model is divided into ranges, where turbulence is generated by different mechanisms: current velocity shear (P^τ), surface waves (P^w) and wave breaking (P^{br}). Additionally, generation mechanisms are introduced into the second range by Stokes drift (P^S) and LC (P^L). In the third range (inertial), turbulence is not generated, but is transferred along the spectrum from small to large wave numbers. A corresponding amount of energy (E) circulates in each of these ranges. Fig. 3 presents a schematic calculation in this model of generation, energy transfer across the spectrum and dissipation (ε).

To take into account the Stokes drift, a number of researchers propose a simple additive relation, which considers the increase in the total velocity shear:

$$P^{\tau} = \nu_t \left(\frac{\partial (U + U_{\mathrm{S}})}{\partial z} \right)^2 .$$

Fig. 4 presents the results of calculations using an improved multiscale model for a specific case. We can see from the figure that consideration of the Stokes drift effect on the dissipation rate changes the dependence form. The calculations with real input parameters obtained in measurements (wind velocity, height and frequency of the spectral wave peak) show that this mechanism adds from 2 to 17% to the total rate of turbulent energy dissipation over a 30-meter layer.



F i g. 4. Turbulent energy dissipation rate ε calculated by the multiscale model [6] with no account for the Stokes drift (red curve) and with account for the Stokes drift (green curve). Dots are the experimental data; V_{10} is the wind velocity at 10 m height; H_{s} is the height of significant waves; f_{p} is the frequency of spectral peak of sea waves

A comparative analysis of experimental data obtained by the above-mentioned set of measuring equipment with calculations using a multiscale model [6] showed that the LC inclusion in the model as a source of turbulence leads to an improved agreement between calculations and measurements. Unfortunately, insufficient knowledge of LC mechanism does not allow the use of any generally accepted parameterization method at this stage. Various authors [26–29] propose different methods for taking this mechanism into account in models. The turbulent Langmuir number introduced in [30] is usually considered as the main parameter:

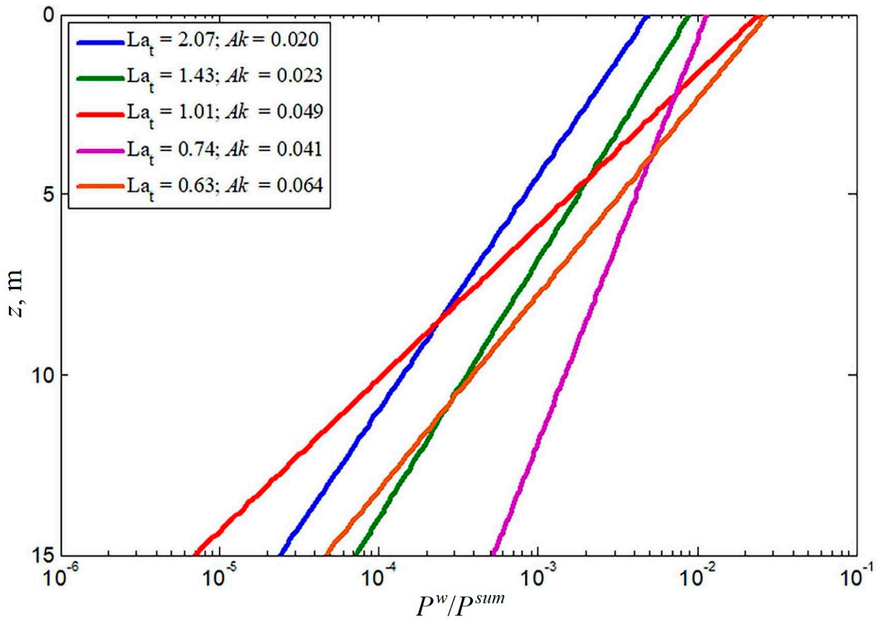
$$\mathrm{La}_t = \sqrt{\frac{u_*}{U_{S0}}},$$

where u_* is friction velocity in water; U_{S0} is Stokes drift at the surface.

The Langmuir number characterizes the relative effect of wind-induced velocity shear and Stokes drift shear on boundary layer turbulence. Stokes drift is determined by the following formula:

$$U_S = A^2 k\omega \exp(-2kz),$$

where A, k and ω are amplitude, wave number and frequency of waves, respectively; z is depth.



F i g. 5. Dependence of the relative contribution of surface wave generation upon the turbulent Langmuir number for real hydrometeorological conditions [25]. *Ak* is wave steepness

Of all the LC parameterizations we considered, the formula proposed in [29] turned out to be the most suitable:

$$\frac{< w'^2 >}{u_*^2} = \begin{cases} 0.398 + 0.48\mathrm{La}_{SL}^{-4/3}, & \mathrm{La}_{SL} \le 1 \\ 0.64 + 3.50\exp(-2.69\mathrm{La}_{SL}), & \mathrm{La}_{SL} > 1 \end{cases}, \tag{1}$$

where w' is vertical velocity fluctuation; u_* is dynamic velocity in water; La_{SL} is Langmuir number calculated from the Stokes drift averaged over the top 1/5 of the mixed layer. In our experiments, the LC contribution to the total turbulization could reach 15% (at $\mathrm{La}_t = 0.63$).

One of the differences of this multiscale model is presence in the turbulent energy balance equation of an additional term that describes turbulent transfer of wave kinetic energy to the lower layers as a result of interaction of surface waves and turbulence [31]. The original version of the model used dynamic velocity u_* as velocity fluctuation scale. Consideration of Langmuir circulation in the form of formula (1) leads to the dynamic velocity replacement by $\sqrt{< w'^2 >}$. As noted in [30], in the wave layer the ratio $< w'^2 > / u_*^2$ can reach 1.8.

Fig. 5 presents the results of calculations with real hydrometeorological conditions for the relation of generation rate by wave movements to the total generation rate of turbulent energy P^w/P^{sum} taking into account dependence (1) at different Langmuir numbers. That is, an increase in the vertical velocity of wave kinetic energy transfer leads to an increase in the effect of waves on the overall turbulence generation. In a certain sense, a decrease in the Langmuir number characterizes an increase in the steepness of surface waves Ak, i.e. an enhancement of nonlinear effects in wave motions, which leads to an increase in the overall layer turbulization.

2.2. Modeling of dynamics of the thermocline upper boundary

Insufficiently accurate parameterization of turbulent mixing of the upper mixed layer of the ocean often leads to noticeable systematic errors in determining the mixed layer depth and the values of ocean surface temperature in global climate models. In our studies we carried out field observations of thickness dynamics of this layer under effect of storm conditions and made an attempt to simulate this process. The one-dimensional Kraus – Turner model of seasonal thermocline [32], which was supplemented with relations for calculating turbulence generation from the multiscale model [6], was taken as a basis.

As is known, the Kraus – Turner model is a system of equations that describe the seasonal thermocline upper boundary evolution under the effect of heat flows and mechanical mixing:

$$\begin{cases} \dfrac{dT_s}{dt} = \dfrac{2}{h^2}\left[\left(S+B\right)h - \left(G - D + \dfrac{S}{\beta}\right)\right] \\ \Lambda \dfrac{dh}{dt} = \dfrac{1}{\left(T_s - T_h\right)h}\left[2\left(G - D + \dfrac{S}{\beta}\right) - \left(S+B\right)h\right], \end{cases}$$

where T_s is sea surface temperature; T_h is temperature at depth h; h is initial position of the thermocline boundary; S is insolation; B are heat fluxes (effective radiation of the sea surface, heat loss due to evaporation, contact turbulent exchange with the atmosphere); G is mechanical mixing contribution; D is energy dissipation; β is a scale factor characterizing the decrease in the energy of penetrating solar radiation with depth.

The Kraus – Turner model upgrade consisted in a more detailed representation of the contribution of mixing mechanical energy, which was calculated as

$$G=\frac{1}{g\alpha}\int_0^z\left[P^\tau(z)+P^w(z)+qP^{br}(z)\right]dz\,,$$

where the terms in the integrand describe turbulence generation by velocity shear P^τ, surface waves P^w and breaking waves P^{br}, q is breaking probability; g is gravitational acceleration; α is thermal expansion coefficient. To calculate these components of turbulent energy, we used the following relations [6]:

$$P^\tau=\nu_t\left(\frac{dU}{dz}\right)^2;\qquad P^w=\sigma_w u_*\frac{dE_w}{dz};\qquad P^{br}=C_{br}\frac{u_0^3}{b_0}\left(1+C_j\frac{z}{b_0}\right)^{-2.8},$$

where ν_t is turbulent viscosity coefficient; u_* is friction velocity in water; κ is von Karman constant; U is drift current velocity; E_w is kinetic energy of waves; b_0 is width of breaking wave crest; σ_w, C_{br}, C_j are constants.

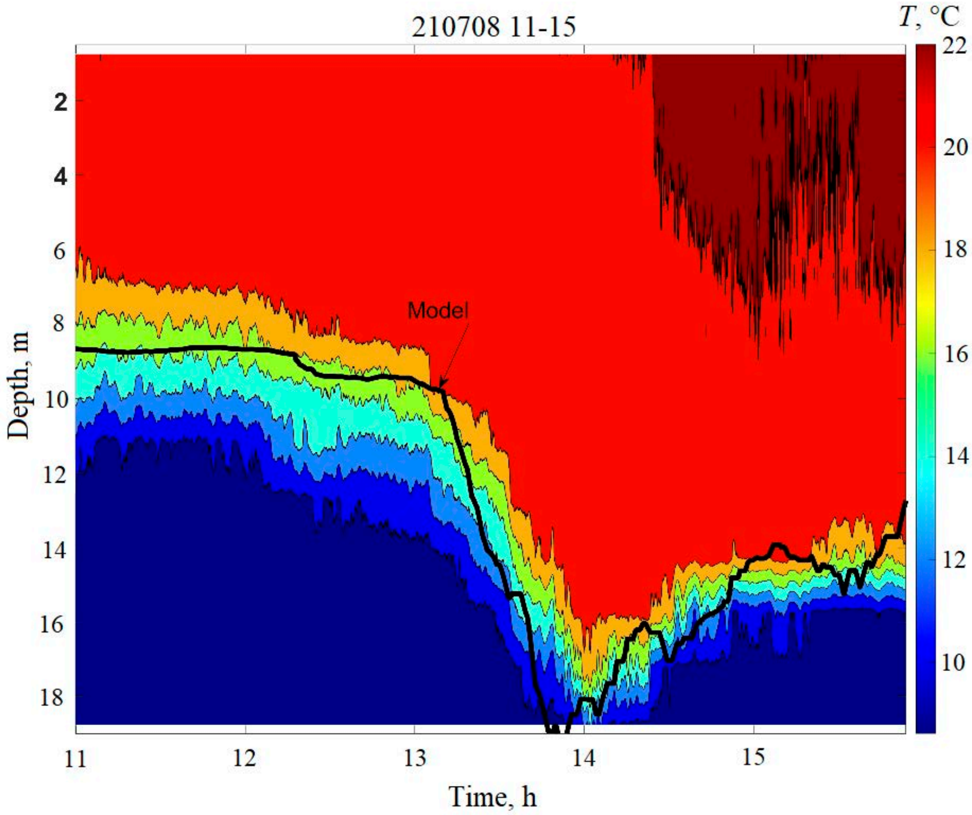
Parameterization of heat fluxes takes into account the effects of insolation, effective radiation of the sea surface, evaporation and contact turbulent exchange in accordance with Shuleikin empirical formulas [1].

Solving the equation system relatively to dh enables us to determine the position of the thermocline upper boundary. The main emphasis at this stage was on assessing the effect of storm-caused turbulent mixing on the deepening of the seasonal thermocline upper boundary. Model calculations were verified using experimental data obtained by our own measurements and the data kindly provided by P.V. Gaisky from a thermoprofiler installed on a stationary MHI platform. It was assumed that the main mixing factor is turbulence, which is generated by the mechanisms described above under wind effect.

An example of a model profile (black curve) and thermoprofiler data is shown in Fig. 6.

The results of calculations based on *in situ* hydrometeorological data reveal that the Kraus – Turner model, supplemented by relations from the multiscale model, corresponds to the actual change in the thickness of the upper boundary layer quite satisfactorily. The correlation coefficient of model calculations of the temperature profile evolution with *in situ* data in most cases was within the range of 0.7–0.9. The discrepancy between observations and model calculations, in addition to the model imperfection, may be caused by the impact of unaccounted factors affecting vertical exchange. These factors include both local currents (cyclonic and anticyclonic) occurring in the coastal zone, as well as upwelling/downwelling processes and convection.

[1] Shuleikin, V.V., 1968. *Physics of the Sea*. Moscow: Nauka, 1083 p. (in Russian).



F i g. 6. Smoothed model curve of dynamics of the upper boundary thickness of seasonal thermocline (black curve) during the storm passage on July 8, 2021 and experimental data obtained by a thermoprofiler. Correlation coefficient between the smoothed model data and the *in situ* measurements is ~ 0.9

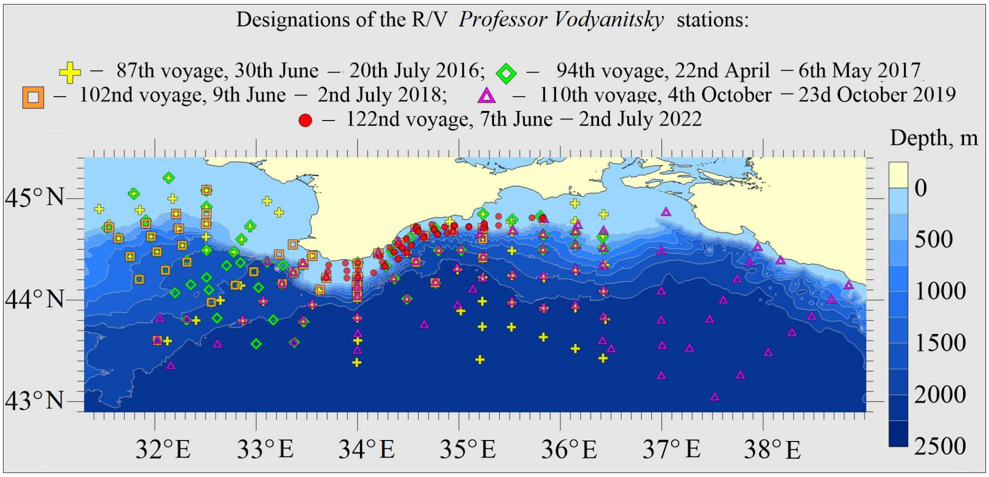
3. Vertical exchange in stratified layers

3.1. Area and period of study

To obtain relations for practical estimates of diffusion coefficients in stratified sea layers, to study the effect of main factors, including stratification parameters and physical-geographical conditions, on the turbulent regime, detailed experimental studies of fine and microstructure of hydrophysical fields at different depths and in different seasons are required. Such studies were carried out by the Turbulence Department employees during the expeditions on research vessels in the Black Sea.

In this work, we used the results of hydrological measurements and data on microstructural profiles of hydrophysical fields obtained during the 87th, 94th, 102nd, 110th and 122nd cruises of R/V *Professor Vodyanitsky* for 2016–2022. The location of the performed stations is given in Fig. 7. The work on collecting data on the microstructure of hydrophysical fields was carried out by the Turbulence Department employees. The information collection was carried out in the northern part of the Black Sea within the economic zone of Russia in order to determine the characteristics of vertical turbulent mixing and background characteristics of the environment in the region under study.

On the 122nd cruise, for the first time we obtained information not only on the velocity and temperature pulsation characteristics, but also on the vertical distribution of oxygen, chlorophyll a and turbidity contained in the water down to depths of more than 900 m due to a new microstructural probe. In general, the analyzed data cover spring – summer – autumn periods, which enable us to draw certain statistical conclusions. In this region, the research included obtaining the dependences of vertical turbulent diffusion coefficient K on the buoyancy frequency N and on the depth z based on the velocity fluctuation characteristics and comparing them with hydrological data at the corresponding stations, as well as general analysis of the hydrophysical features of the study areas and their surroundings.



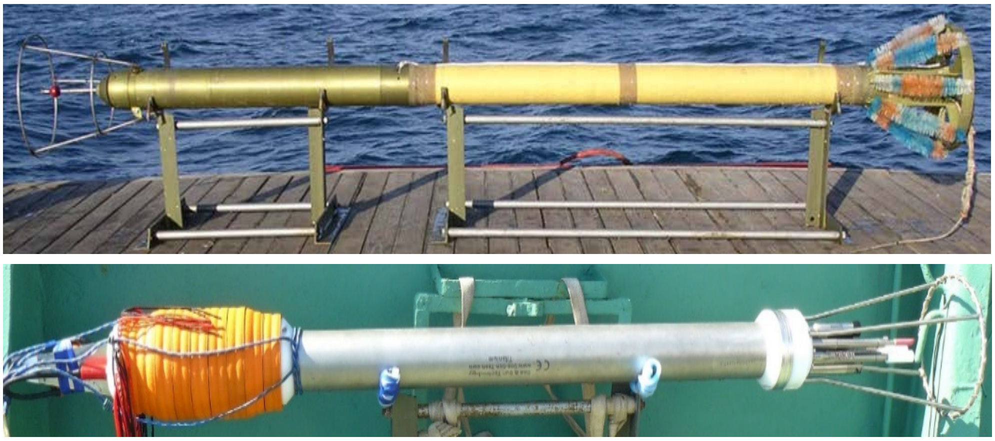
F i g. 7. Map of the performed stations over the whole analyzed period of measurements

A comparison of experimental data with known turbulence models showed that the best agreement between calculations and measurements is provided by the 1.5D model, which takes into account the average area of the basin varying with depth. The model assumed that variability of the main turbulent mixing characteristics with depth depends on the dominant source of turbulence at given horizons.

3.2. Instruments and methods

In the performed studies, the survey of background hydrological characteristics was carried out by the MHI expeditionary support group members via CTD SBE 911plus and Idronaut Ocean Seven 320 PlusM complexes.

In 2016–2018, Sigma-1.5 complex [33] was applied as a microstructural measuring probing instrument. In Sigma-1.5 complex, the registration of fluctuating hydrophysical quantities was carried out in a free fall mode in the water with 0.7 m/s velocity down to a given depth (maximum up to 300 m). In 2022, MSS90L complex was applied, a multi-parameter microstructure probe equipped with sensors for turbidity, temperature, salinity, velocity shear, oxygen, pressure and natural vibrations (accelerometers with a gyroscope), which can operate down to 1000 m depth (Fig. 8).



F i g. 8. Sigma-1.5 (*top*) and MSS90L (*bottom*) microstructure probes

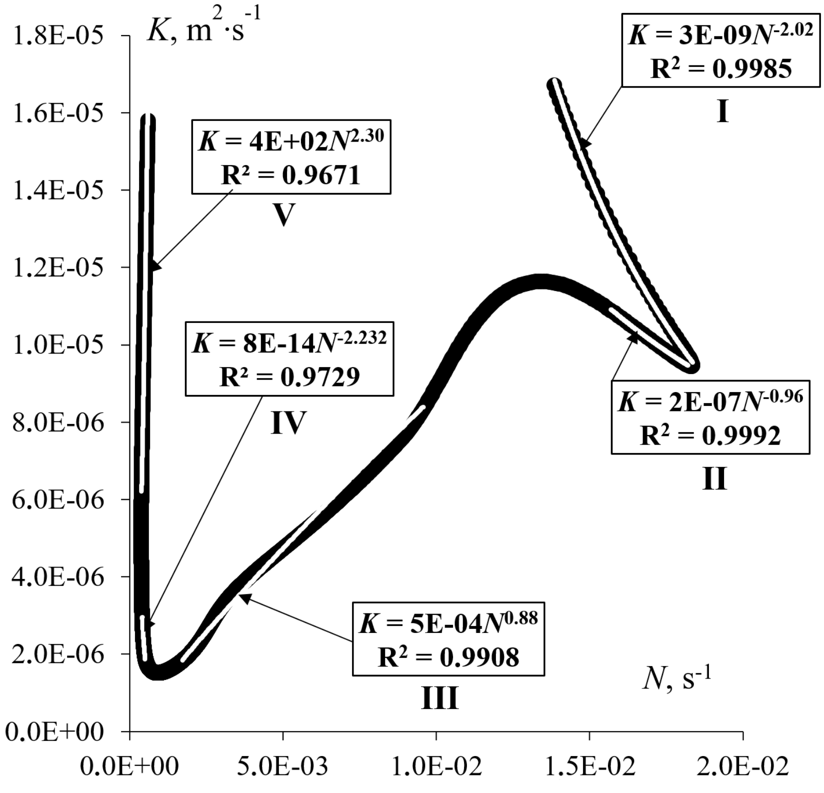
The microstructural sensor of Sigma-1.5 complex directly measures three components of the velocity vector fluctuations (sampling frequency 100 Hz), while MSS90L measures the vertical gradient of horizontal velocity fluctuations ($\partial u/\partial z$, $\partial v/\partial z$, further all formulas will refer to both components) with a sampling rate of 1024 Hz. The vertical component is not considered due to high velocity of the device itself along the vertical axis. In order to reduce the effect of emissions and noise caused by device vibration, hardware currents and the microbiota impact on the sensitive elements of sensors, appropriate algorithms were used to remove them and then a bandpass filter was applied to remove noise of high (Kolmogorov wavenumber limitation) and low (limitation on the inertial subrange of turbulence spectrum) frequency. Turbulent energy dissipation rate was determined by the relation $\varepsilon = \frac{15}{2}\nu\left[\overline{(du/dz)^2}\right]$, where ν is kinematic viscosity. The dispersion $\left[\overline{(du/dz)^2}\right]$ was calculated by integrating spectrum gradient values of horizontal velocity fluctuations in the selected range of wave numbers using the Welch method. This method enables us to estimate ε with good vertical resolution; here we limited ourselves to a resolution of 2 m. The quality of the obtained fluctuation spectra was assessed by the average absolute deviation from the Nasmyth model spectrum [34].

Estimation of ε was also carried out by the method described in [35] according to the relation $\varepsilon \cong 0.1 \cdot L^2 N^{-3}$ where L is effective vertical scale of the mixed patch for a fixed depth interval, which was determined from the stable minimum in the small-scale region of temperature vertical gradient spectrum [36]. The buoyancy frequency N (Väisälä – Brunt frequency) as the main parameter characterizing density stability is determined by the formula $N = \sqrt{\frac{g}{\rho}\frac{\partial\rho}{\partial z}}$. The calculation by this method was carried out at 10-m depth intervals for a limited number of stations within the Kerch section of the shelf in the area of a sharp continental slope.

The vertical turbulent diffusion coefficient is calculated by the following formula:

$$K \cong \frac{R_f}{1-R_f}\frac{\varepsilon}{N^2},$$

where R_f is dynamic Richardson number (the ratio of potential energy increase rate in a system to the input rate of energy spent on mixing). In this work, R_f value was taken equal to ¼ in accordance with the approximate result from [37].



F i g. 9. Dependence of the vertical turbulent diffusion coefficient K on buoyancy frequency N in the stratified layers within the depth interval 50–1750 m for the Black Sea deep part [21]

3.3. 1.5D model

Based on a large amount of experimental data and model developments in previous studies, a number of important results characterizing the features of vertical turbulent exchange in the Black Sea stratified layers was obtained. These results enabled us to establish a power-law dependence of the heat and salt diffusion coefficient on the buoyancy frequency N for the deep-water part of the studied basin. The indicators of this power function $K \cong A \cdot N^{\alpha}$ are determined by the nature of internal waves in a particular medium, but also depend on the bottom topography features [38]. The model dependence $K(N)$ itself (black line) with approximations (white lines) for the selected layers is presented in Fig. 9.

As the analysis result, we identified five stratified layers with vertical turbulent exchange features characteristic of them, which are described in detail in [21]:

Layer I. It is located within the depth interval of 50–70 m and represents the lower active layer (cold intermediate), located in close proximity to the upper active layer, which serves as a source of various disturbances for it and, as a consequence, causes formation of internal waves in it. As these waves break, they maintain turbulent exchange in the layer. Another source of turbulent exchange here is quasi-inertial internal waves (quasi-horizontal stratified unstable currents), their local breaking form turbulent patches [12].

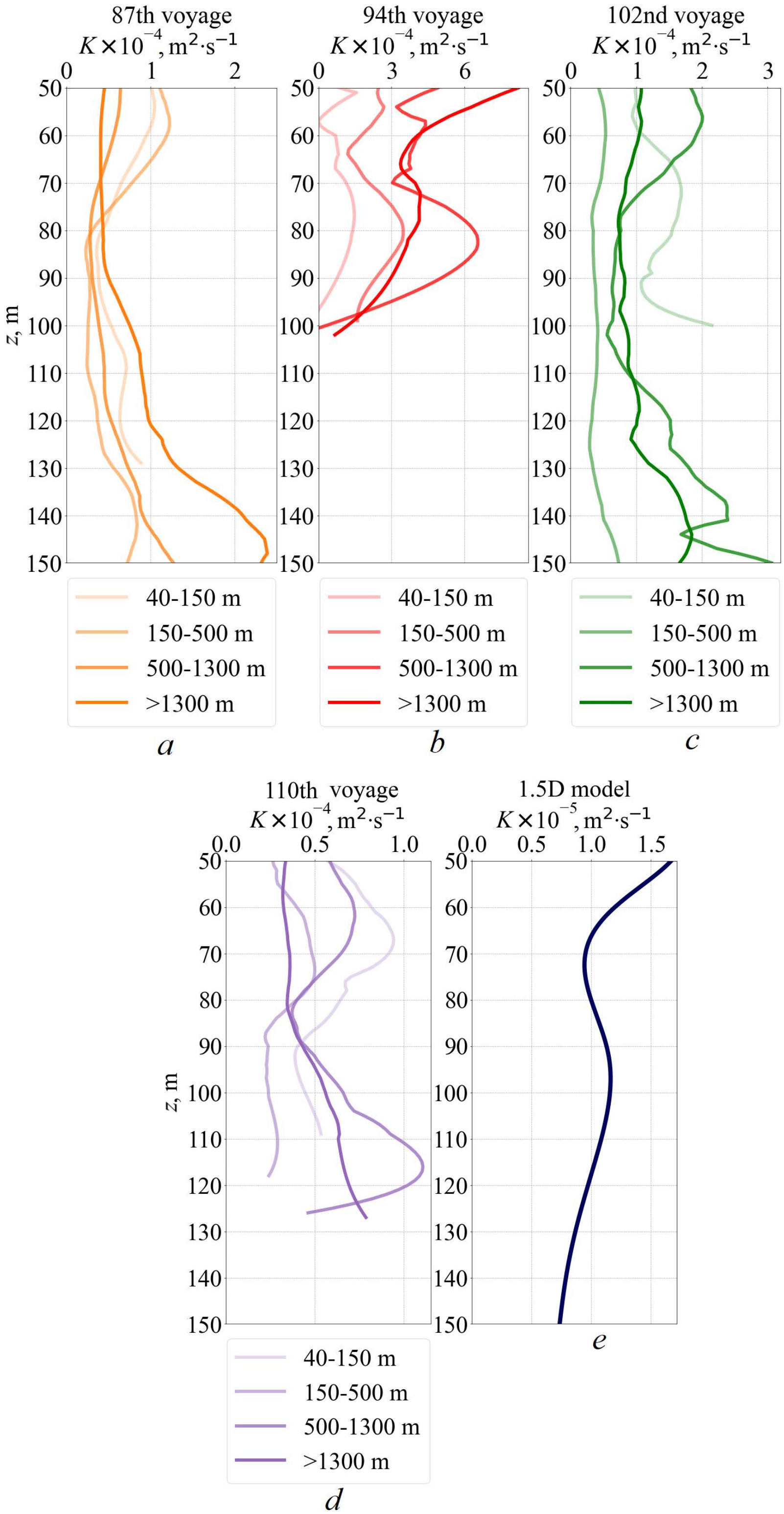
Layers II–III. They are located in depth intervals from 70 to 100 m and from 130 to 650 m, respectively, with a transition zone between them, representing the main pycnocline of the basin under study. As was found in [39], vertical turbulent exchange is maintained here due to the shear instability of radial quasi-inertial internal waves (quasi-horizontal currents). The difference between these layers is in stratification: the upper one is weakly stratified and the lower one is highly stratified. The characteristic scales of waves in the second layer, which transfer their energy into turbulence, also depend on the derivative of buoyancy frequency function N.

Layer IV. A possible hydrophysical mechanism for turbulent exchange in this deep-sea layer is intrusive layering in the lower stratified layer caused by geothermal heat flux from the sloping basin floor. This layer lies within 1350–1550 m depths. The space between layers III and IV is a transition zone with a decrease in the effect of some mixing mechanisms and an increase in others, but with a different power-law dependence.

Layer V. The last of the considered layers is located within 1600–1750 m interval and is exactly adjacent to the bottom homogeneous layer considered in [40] (not shown in the Figure). Vertical structure formation in this stratified layer is mainly determined by the combined effect of two factors: heat, which continuously comes from the bottom and maintains the homogeneous layer stationarity, and increased salinity values due to the inflow of the Lower Bosphorus Current salty waters into the lower layers.

3.4. Results

Based on the results of Sigma-1.5 sounding complex measurements and calculations, spatial distributions of K and N were obtained for the upper hundred-meter layer with a depth interval of 3 m. Averaged dependences were analyzed for the stations at the location of which the sea depth is within four ranges: from 0 to 150; from 150 to 500; from 500 to 1300; more than 1300 m (in accordance with the presence of possible effects described in [21]). Fig. 10 gives the profiles for the corresponding depth ranges.



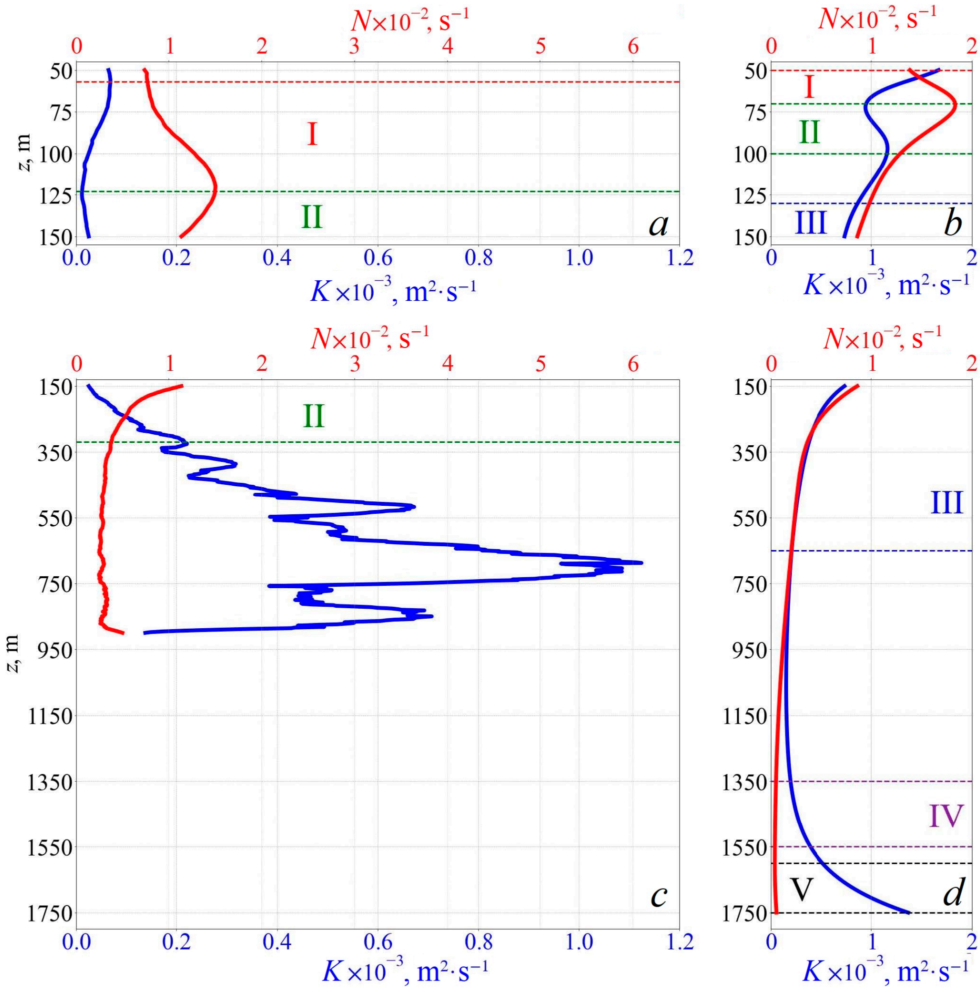
F i g. 10. $K(z)$ profiles resulted from the measurements (*a* – *d*) and 1.5D model calculations (*e*)

As can be seen from the graphs, as we move away from the shelf zone and the station location depth increases, there is a transformation of the profile, which repeats the model distribution of K with its characteristic inflection points but with larger coefficient values. This is especially seen in the example of the 94th cruise, where the data were collected mainly in the northwestern part of the region under study and in the area of sharp continental slope near the Kerch section of the shelf. With an increase in the number of stations performed away from the shelf slope and over the deep-water part of the Black Sea (87th, 102nd, 110th cruises), K variation with depth approaches the model range of values – about 10^{-5} $m^2 \cdot s^{-1}$. This indicates a decrease of the inclined bottom effect with increasing depth on the overall picture of turbulent mixing within depth ranges of 500 m and more, which confirms a significant impact of effects described in [11] on the exchange processes in the Black Sea upper stratified layers.

Fig. 11 demonstrates a comparison of model distribution $K(z)$, $N(z)$ and the measurement results obtained during the 122nd cruise of R/V *Professor Vodyanitsky*. The upper axis of the graphs indicates buoyancy frequency values (red curve), and the lower axis – K (blue curve). The coefficient values calculated from the environmental parameters measured by MSS90L complex (Fig. 11, *a*, *c*) are in this case two orders of magnitude higher than the values resulted from 1.5D modeling (Fig. 11, *b*, *d*). The calculated values were obtained with a depth discreteness of 2 m and were averaged over all stations for the corresponding depth ranges followed by the Savitzky – Golay filter application for highlighting the main trend in the variation of these values with depth.

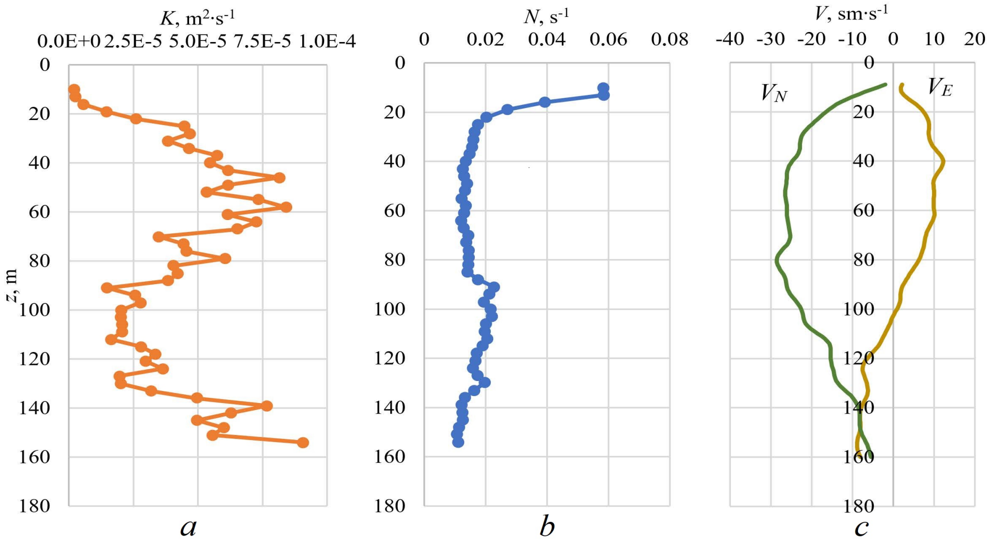
Due to the political situation in the country, in 2022, during the 122nd cruise, the measurements were carried out only in the territorial waters of the Russian Federation within 12-mile coastal zone, which mainly fell on the areas of the Kerch section of the shelf and the continental slope near the Southern Coast of Crimea. The calculation results based on the new data showed a very good correlation with the model ones in the area of the main and seasonal thermoclines up to the convergence in the power part of approximation dependence $K \cong CN^{\alpha}$. For layer I $\alpha \approx -2$, for layer II $\alpha \approx -1$. In the five layers identified in the model distribution (Fig. 11, *b*, *d*), experimental dependences correspond to the approximations from Fig. 9. However, there are at least three conditional layers where the coefficient values differ from the model ones. These layers differ in the turbulence generation intensity, which is determined mainly by shear instability, and depend on various hydrophysical factors.

For earlier measurements, the power values in the approximation dependencies varied from $\alpha = -1.5$ to $\alpha = -2.3$, on average giving a result close to $\alpha \approx -1.8$ over the set of measurements. The C coefficients differ significantly by several orders of magnitude. Such differences are due to special hydrological regimes in the depth ranges under consideration, as noted earlier in [41], and the fact that several conventional depth regions, where mixing is carried out by various physical mechanisms, are covered. During the 94th cruise, which took place in late spring – early summer, the exponents varied depending on the place depth from $\alpha = -1.9$ to α = –2.6, on average α ≈ –2.2. In the 102nd summer cruise α = –1.6…–2.7, which is also on average α ≈ –2.2. However, for the autumn 110th cruise, the order of *C* coefficient values and the dependence exponent changed: α = –0.7…–2.3 with an average value for the region under study α ≈ –1.5, which is due to a change in the general hydrological regime in it.



F i g. 11. $K(z)$ and $N(z)$ profiles resulted from the measurements in the 122nd cruise of the R/V *Professor Vodyanitsky* (*a*, *c*) and 1.5D model calculations (*b*, *d*)

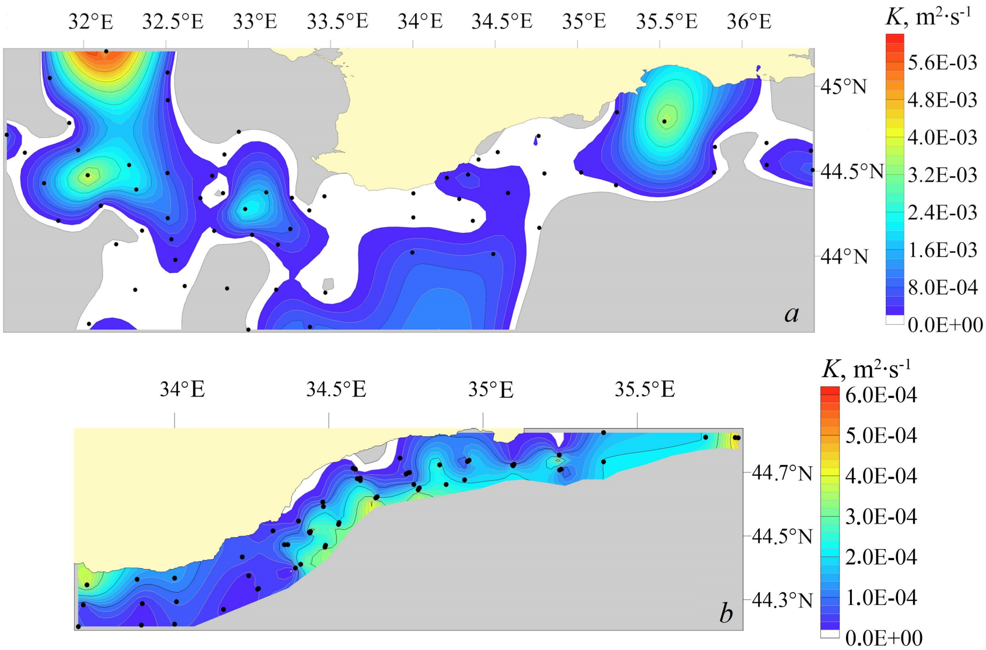
The calculation gave ambiguous results for a number of stations with an uneven distribution of the coefficient over depth with a strong scatter in values, which can be explained by the feature of horizontal currents [42]. However, more statistical data is required for a more accurate answer. An example of comparison of calculation results with actual current velocities at such a station can be seen in Fig. 12. As it is obvious from the figure, the maximum coefficient values are in the layers from 40 to 70 m and from 140 to 160 m. In the depth range of interest (up to 100 m), a current with the highest velocity values is recorded in the depth range from 40 to 70 m (the same range where maximum K values take place). At some stations, calculation results showed abnormally high values of K (Fig. 13) reaching values of the order $10^{-4} \div 10^{-3}$ $m^2 \cdot s^{-1}$. It can be assumed that in these cases there were some local mechanisms for turbulence generation, which lead to such anomalous results. The nature of the noted anomalies has not yet been clarified.



F i g. 12. Distribution of K (*a*), N (*b*) and current velocities (*c*) with depth based on the calculation results and ADCP measurement data at station 10 of the 87th cruise of the R/V *Professor Vodyanitsky*. V_E and V_N are zonal and meridional current velocity components

In the same way, a number of spatial distribution maps of average, minimum, and maximum values of K and N were obtained along with the maps of location depths of these values for each of the cruises. It enabled us to draw a number of important conclusions when compared with the results of other works [43–46]. The results of expedition data analysis revealed that the most probable cause for the increase in K values is the combined effect of several factors intensifying turbulent mixing: the stations were located in the action zone of anticyclonic branches or in the zones of intermittency of cyclonic and anticyclonic eddies formed under the effect of the Rim Current [20]. In most cases the increased turbulence intensity is observed at stations located near the shelf edge or above the continental slope in the area of a sharp drop in depths, which can be caused by the processes described in the work [20].

When comparing the results with currently known hydrological data [43–46], we established a relationship between the depth of K maximum and the penetration depth of the upper mixed layer, the cold intermediate layer depth and the vertical temperature gradient maximum: the higher the cold intermediate layer and the maximum rise gradient, the closer the maximum K will be. At the same time, the lower the boundary of the upper mixed layer is located, the higher the maximum values of K will lie. This also explains the anomalous K values at some stations, since these factors are combined here: large depth of the upper mixed layer (up to 50 m near the Kerch Peninsula) with a relatively small depth of the cold intermediate layer (~ 70 m above the shelf).



F i g. 13. Average values of K at the stations of 94th (*a*) and 122nd (*b*) cruises of the R/V *Professor Vodyanitsky*. Dots indicate performed stations

4. Conclusion

The presented results are a certain generalization of the research carried out by the employees of MHI Turbulence Department in recent years. Basically, the work was carried out in two directions: the study of turbulent processes in the upper mixed layer directly bordering the atmosphere and the study of turbulent exchange patterns in stratified layers. All parameterizations and semi-empirical relationships are based on large amounts of experimental data collected during the research over a number of years.

Insufficiently adequate understanding of interaction processes between the atmosphere and the ocean, simplifications in modeling turbulent exchange in the upper mixed layer lead to significant errors in calculating the mixed layer depth and ocean surface temperature. The performed studies of turbulence in the sea surface layer, taking into account Langmuir circulations and improving the multiscale model of turbulent exchange, develop our understanding of vertical mixing mechanisms and increase objectivity of model calculations. Methods for studying LC using various instrumental means have been tested and a number of important characteristics required for parameterizing this phenomenon have been obtained. It is demonstrated that a more detailed determination of the magnitude of turbulent energy generation by various mechanisms provides the application of relatively simple models of the dynamics of mixed layer thickness with greater accuracy. The Kraus – Turner model, supplemented by calculations using a multiscale turbulence model, quite satisfactorily describes the deepening of the seasonal thermocline upper boundary during the passage of a storm.

The studies of turbulent exchange patterns in stratified layers are important for assessing the vertical fluxes of heat, salts, dissolved chemicals, including nutrients. The diapycnic transport, caused by the dynamics of internal waves and their breaking, is the most important mechanism for ventilation of deep layers in the water column. The obtained model and semi-empirical dependencies make it possible to estimate the vertical exchange intensity at various horizons, taking into account the features determined by physical-geographical conditions and the dominant mechanisms of turbulence generation. Detailing the stratification conditions in the deep layers of the Black Sea and identifying five layers with different dominant mechanisms of turbulence generation increases the accuracy of practical estimates of turbulent diffusion vertical coefficient and provides the application of these results in large-scale water circulation models and balance calculations of heat and salts of the entire basin.

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Aleksandr M. Chukharev – formulation of the research problem, review of literature on models of turbulent exchange in the upper mixed layer of the ocean, carrying out the experiments, development of the multiscale model, creation of software and model calculations, analysis of the study results and their description, formulation of conclusions, writing and preparing the paper for publication

Dmitry A. Kazakov – carrying out experiments, data processing and analysis, analyzing the results of calculations and their interpretation, graphing, discussing the results, formulating conclusions, writing and preparing the paper for publication

Mikhail I. Pavlov – development of research methodology, literature review on Langmuir circulations, experimental research, development of processing program, data processing, analysis and interpretation of results, paper writing

Vladimir A. Korzhuev – literature review on mixed layer models, carrying out the experiment, data processing and analysis of results, development of computer programs, calculations on multiscale and Kraus-Turner models, interpretation of results, paper writing

The authors have read and approved the final manuscript.
The authors declare that they have no conflict of interest.