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Model and Experimental Estimates of Vertical Mixing Intensity in the Sea Upper Homogeneous Layer

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Purpose. The study is aimed at qualitative and quantitative analysis (based on the updated previously proposed multiscale model) of the experimental data on turbulence intensity and their comparison with theoretical and semi-empirical relationships for the purpose of describing the contributions of various turbulence sources.

Methods and Results. A comparative analysis of experimental data and model calculations of turbulence characteristics near the sea surface was performed. The methods of theoretical assessing generation of turbulence in the near-surface sea layer by various physical processes are considered. The results of calculations by the well-known models of turbulent exchange were compared with the experimental data collected by the scientists of the Turbulence Department of MHI, RAS, using the specialized equipment. The analysis results made it possible to determine the possibility of applying the considered models for calculating turbulence intensity under different hydrometeorological conditions. At light winds, none of the models yielded the results which matched the measurement data. At moderate winds, the simulation results showed quite satisfactory agreement with the experiment data; and for strong winds, the multiscale model results were the best. This model was modified to assess the contributions of two other mechanisms of turbulence generation: the Stokes drift and the Langmuir circulations.

Conclusions. Objective assessment of the turbulent exchange intensity requires taking into account of three main mechanisms of turbulence generation, namely flow velocity shear, wave motions and wave breaking. Depending on the hydrometeorological situation, each of these mechanisms can dominate in a certain depth range. The calculations performed using the updated model showed that the Stokes drift added 2–17 % to the total dissipation in the upper 30-meter layer, whereas the contribution of the Langmuir circulations calculated through dependence of the vertical velocity of kinetic energy transfer upon the Langmuir number, can reach 15 % for small Langmuir numbers.

Keywords: turbulent exchange, upper sea layer, turbulence generation mechanisms, modeling, dissipation rate, model verification, multiscale model, Stokes drift, Langmuir circulations

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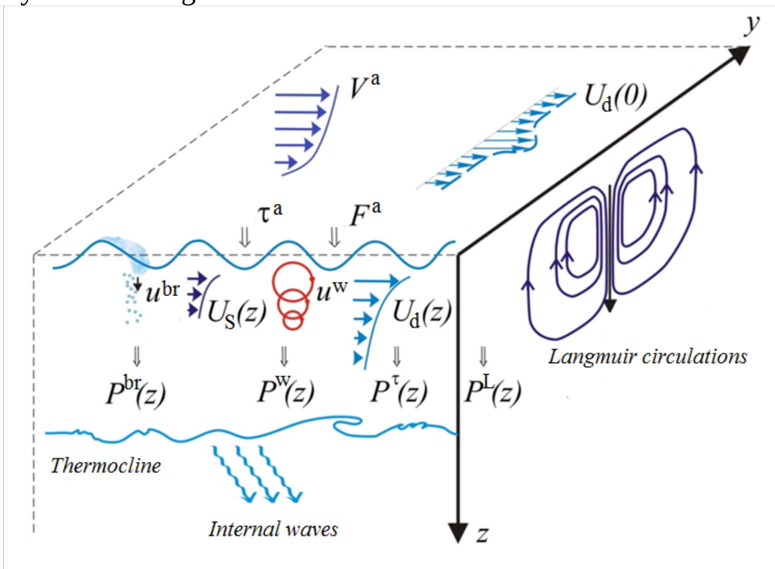
Introduction

The semi-empirical theory of turbulence considers the key parameters for describing dynamic processes in the upper mixed layer of the sea as the coefficients of turbulent exchange, varying over a very wide range depending on hydrometeorological conditions. Determination of these dependencies is still one of the most urgent problems in modern oceanology. Insufficient knowledge of the physical processes in this sea layer leads to the fact that the calculation results using predictive models for the upper layer may differ greatly from the actually observed values of such characteristics as the surface temperature and the mixed layer depth.

The most important mechanisms for turbulence generation in the upper layer of the ocean are as follows: 1) instability of vertical velocity gradients in drift currents, called for brevity the velocity shear; 2) instability of movements induced by surface waves; 3) breaking waves [1]. Convective instability and Langmuir circulations are considered not always significant sources of turbulence; therefore, many authors do not take them into account in their models. Nevertheless, Langmuir circulations have recently been actively included in calculations to increase the reliability of theoretical models describing the vertical mixing intensity in the upper layer [2]. According to a number of researchers, the inclusion of this mixing mechanism in large-scale models of ocean-atmosphere interaction will significantly improve the objectivity of theoretical calculations [1].

Main sources of energy input to marine turbulence in the near-surface layer are schematically shown in Fig. 1.



F i g. 1. Main mechanisms of the sea turbulence generation in the near-surface layer: V^a – wind speed; U_d – drift current speed; τ^a and F^a – momentum and energy fluxes from the atmosphere; U_S – the Stokes drift; u^w – velocity of orbital motion in a wave; P^τ, P^w, P^{br}, P^L – energy influx to turbulence from different sources

Historically, the main role among the turbulence generation mechanisms in the near-surface layer of the ocean (according to K.N. Fedorov's definition, this layer is up to a depth of 10–30 m [3, p. 8]) was assigned to both surface waves (in models [4–6]) and the drift current velocity shear [7]. Later models [8, 9] took into account, first, the breaking of surface waves as a source of turbulence, the second most important was the drift current velocity shear. In the multiscale model [10], all of the aforementioned generation mechanisms are considered, although it is noted that in some hydrometeorological situations none of the models, including the proposed one, gives good agreement with the experimental results in the calculations. A possible reason for the discrepancy between the results of model calculations and

[1] Chukharev, A.M., 2019. [Influence of Various Mechanisms of Turbulence Generation on the Vertical Exchange Intensity near the Sea Surface]. In: MHI, 2019. [*Seas of Russia: Fundamental and Applied Research. Sevastopol, 23-28 September 2019*: proceedings of conference]. Sevastopol: MHI, pp. 317-319 (in Russian).

measurement data is, in particular, the absence of such sources of turbulence as LC and microbreakings in the model. In addition, there is quite a lot of evidence for the existence of submesoscale spatial structures that can significantly affect both the intensity of turbulent exchange processes in the boundary layers of the sea and the atmosphere and the interaction between the two media.

Langmuir circulations are pairs of cylindrical vortices alternating with each other with right- and left-hand movement, carried out relative to horizontal axes parallel to each other and directed approximately along the normal to the wind wave front. Langmuir circulations appear as a result of the interaction of the Stokes drift induced by surface waves with a vertical shear in a turbulent fluid, which creates a eddy force described in the Craik – Leibovich model [11]. Stripes of foam or "paths" of floating objects on the water surface are considered a sign of the Langmuir circulations existence in a reservoir [2]. Characteristic features of Langmuir bands: appearance at a certain wind speed; their orientation coincides with the wind direction; when its direction changes, the bandsquickly line up along the wind; they have a relative periodicity in space and are distributed over a vast area. Langmuir circulations are identified on the reservoir surface on a scale of 2 m – 1 km.

Based on extensive experimental studies, the main characteristics of Langmuir circulations observed by different methods are described in [12], and their intensity is parameterized through the dynamic velocity and Stokes drift. Subsequently, most researchers also used these parameters for a qualitative and quantitative description of the Langmuir circulations features.

According to the 3D modeling results in [13], it was shown that inhomogeneities are formed in the upper boundary layer, and the model resolution permitted to reproduce waves of different scales, up to gravitational-capillary ones. The work [14] describes the turbulent boundary layer observations and the results of modeling large-scale structures associated with this layer dynamics in the coastal zone of the ocean. It was shown that in the Langmuir circulations presence, the vertical transfer of turbulent kinetic energy plays a significant role in its balance. The article [15] theoretically analyzed instabilities arising from horizontal gradients (fronts). Such instabilities (their existence follows from the Craik – Leibovich equations [11]) lead to cross-isopycnic transport. The authors of [15] obtained an unexpected result: Langmuir circulations, being a mechanism of vertical mixing, can lead to the opposite effect – the re-stratification, i.e., maintaining a stable stratification in this layer.

In recent decades, one of the most popular methods for studying eddy structures, including Langmuir circulations, is the Large Eddy Simulation (LES) method. In the study [16], using LES-modeling, turbulent processes in the surface boundary layer of the ocean were analyzed based on observations carried out using the CBLAST program (Coupled Boundary Layers Air-Sea Transfer) in 2003 near the Martha's Vineyard Island. In addition, the relative role of breaking waves and Langmuir circulations in vertical turbulent transport was estimated; the calculation results were in agreement with the experimental data.

A number of works by a group of scientists are also devoted to studies of Langmuir circulations based on LES modeling [17–19]. One of the key parameters in

[2] Sudol'skiy A.S, 1991. Dynamic phenomena in reservoirs. Leningrad: Gidrometeoizdat. pp. 46 (in Russian).

these models is the Stokes drift, which is also used in determining the so-called turbulent Langmuir number. Spatial scales (the authors usually used the term "sub-mesoscale") in the calculations were in the range from 1 m to 10 km. Various problems were considered: the effect of swell on the Langmuir circulations formation, the passing cyclone effect on the structure of the circulations, the change in the pycnocline entrainment rate, etc. play important role in the dynamics of the surface boundary layer. The conditions favoring the convection development also favor the Langmuir circulations existence, and these two processes, apparently, contribute to the mixed layer turbulence.

Thus, a considerable number of studies indicate that when describing the upper boundary layer, along with other mechanisms of vertical mixing (shear velocity, surface waves and their breakings), the Langmuir circulations should also be considered.

Calculating the turbulence generation rate of in models

The most established expression for calculating the turbulence generation rate in shear flows is the formula, which is generally written as

$$P^{\tau} = -\overline{u_i' u_k'} \frac{\partial U_i}{\partial x_k},$$

where U_i are mean current velocity components; u_i' are components of velocity pulsations along the corresponding x_i-coordinates; the bar above denotes averaging; summation is carried out over the repeated indices. Expressing the Reynolds stresses in terms of the turbulent viscosity coefficient ν_t and the mean velocity gradient, for a horizontally homogeneous current, we obtain

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

For near-wall turbulence, the ν_t coefficient is usually taken to be linearly dependent on the distance to the wall, and the current velocity profile is taken as logarithmic.

Despite the fact that another powerful mechanism of turbulence generation – wave breaking – is considered by most researchers to be the most important, it is not so unambiguously defined: various authors propose very different approaches. In the model [8], the effect of breaking waves was parameterized in terms of the turbulence scale (using the Prandtl hypothesis) and the roughness parameter. That is, this mechanism was not explicitly included in the model. In [9], wave breaking, including micro-breaking, is considered as a volume source of energy and momentum, which depends on the spectral composition of surface waves. To calculate the volumetric production of turbulent kinetic energy due to breaking we used the following relation

$$P^{\mathbf{wb}}(z) = \int_0^{\min(k_b, 1/z)} k D_E(\mathbf{k}) d\mathbf{k} \, ,$$

where D_E is the wave pulse dissipation spectrum; k_b is the wave number of the shortest breaking waves; **k** is the wave vector [9].

In the model [10], to estimate the contribution of the breaking waves to the layer turbulization, the penetration under the surface of the breaking part of the wave was considered as the aerated jet propagation in the liquid. The necessary parameters, such as the probability of breaking and the width of the crest of breaking waves, were determined using empirical formulas [21, 22].

In recent years, there have been attempts to consider the effect of breakings based on O.M. Phillips expressions for calculating the characteristics of breang waves using the parameter $\Lambda(c)dc$, which is the length of the breaking front per unit of the sea surface area in the range of wave phase velocities from c to $c + dc$ [23]. The total length of breaking fronts per sea surface unit is calculated as

$$L = \int \Lambda(c)dc,$$

and the mean rate of energy loss per area unit by a breaker moving with a speed ranged from c to $c + dc$ is determined through the fifth moment by the following formula

$$\varepsilon_s(c)dc = bg^{-1}c^5\Lambda(c)dc,$$

where b is the dimensionless parameter characterizing the intensity of breaking ; g is the free fall acceleration. Apparently, this approach is very promising, although the form of the dependence $\Lambda(c)$ and the parameter b remain insufficiently studied [24–27].

The third turbulence generation mechanism is "hydrodynamic instability of wave motions in the upper mixed layer, induced by surface waves" [1, p. 40]. It is not taken into account in many models, although there is strong evidence of the influence of wave motions on turbulence [28–33]. The influence of surface waves on the turbulent regime (without analyzing the actual breakdowns) was discussed in detail in [34]. There it was noted that the main effect of the interaction of waves and turbulence is the vertical transfer of kinetic energy by turbulent motions. In this case, the main role is apparently played by motions comparable in scale with the thickness of the wave layer.

In recent years, ocean circulation models with an additional term that characterizes the effect of wave-induced mixing have been tested [28, 35]. Based on the linear wave theory, the coefficients of turbulent viscosity and diffusion are determined. They are additively introduced into the commonly used KPP (K-Profile Parameterization is the parameterization of the vertical profile of the turbulent viscosity coefficient, usually in the form of a polynomial in the vertical coordinate z [36]):

$$K_m = K_{mc} + B_V,$$

where K_{mc} is calculation in accordance to the scheme [37], and B_V is obtained from

$$B_V = \left\langle l_z^w u_z'^w \right\rangle,$$

where l_z^w – the mixing scale, proportional to the particle displacement in the corresponding direction (in this case, along the vertical), and $u_z'^w$ is the increment in the wave motion velocity on this scale. For a monochromatic wave in [35, p. 1344] displays the ratio

$$B_V = \alpha A^3 k\omega \exp(3kz).$$

Here α is the observation constant; *A* is the amplitude of excitement; *k* is the wavenumber; ω is the cyclic frequency; z is the vertical coordinate directed upwards.

In [31], it was proposed to divide the contribution of wave motions to mixing into symmetric and asymmetric parts: the first replenishes the turbulence energy due to the orbital motion of particles (if the Reynolds wavenumber exceeds the critical value: $\mathrm{Re}^{\mathrm{wave}} > 3000$), the second increases shear generation. The influence of the first component is taken into account in the change in the turbulent viscosity coefficient, the influence of the second is considered as an addition to the flow velocity shear.

In [10], the energy flow to turbulence from non-breaking waves was assumed to be proportional to the kinetic energy of orbital motion and for the plane case (two-dimensional waves) was determined in accordance with [34, p. 1981] as

$$P^{\mathrm{w}}(z) = -\frac{d}{dz}\left(\overline{w'E^{\mathrm{w}}}\right),$$

where $E^{\mathrm{w}} = \frac{\tilde{u}_i \tilde{u}_i}{2}$ is the wave energy (in [34] it was noted that the statistical moments $\overline{\tilde{u}_i^{2n} u_j'^m} \neq 0$; *m*, *n* = 1, 2…); *w*′ is the vertical component of the velocity pulsations. For the calculation in the model [10], the approximate formula was used

$$P^{\mathrm{w}}(z) \approx C_{\mathrm{w}} u_* \left| \frac{dE^{\mathrm{w}}}{dz} \right|, \quad (1)$$

where C_{w} is an empirical constant, determined in the process of model verification; u_* is the dynamic speed in water.

There are no generally accepted model concepts to estimate the LC contribution, the main relations are obtained mainly using LES-modeling. In [12], a parameter called the turbulent Langmuir number was introduced:

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

where u_* is still dynamic speed in water; U_{S0} is the Stokes drift on the surface. In fact, the Langmuir number characterizes the relative influence of wind-induced velocity shear and Stokes drift shear on boundary layer turbulence. Stokes drift is defined by the following formula

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

where A, k and ω – amplitude, wavenumber and frequency of waves, respectively; z is the depth. As shown, the intensity of the vertical transfer of turbulent energy increases with La_t. decreasing. In the upper mixed layer parametrization (KPP), which uses the vertical velocity scaling characterizing the transfer of turbulent energy (in the original works, the term "vertical component of kinetic energy" or simply "vertical kinetic energy", VKE), relations of the following form [38–40] were found

$$\frac{<w'^2>}{u_*^2} = \alpha\left[1 + b\mathrm{La}^{-n}\right], \tag{2}$$

where a, b and n are numeric constants; w' is the vertical ripple of speed. In the waveless layer, the ratio (2) is usually equal to 0.64, while with waves this value can reach 1.8 [38]. In a number of works, the case of a mismatch between the directions of the Langmuir bands wind and waves is also considered, while dependence (2) becomes a little more complicated [41].

In [13, 42], the LC influence is considered only in the generation by the Stokes drift shift, whereas in [43] this influence is considered as an inflow of energy through the boundary. In [33], to calculate the turbulence generation by Langmuir circulations, the formula was used

$$P^{\mathrm{L}} = \nu_t \left(\frac{\partial U}{\partial z}\frac{\partial U_S}{\partial z} + \frac{\partial V}{\partial z}\frac{\partial V_S}{\partial z} \right), \tag{3}$$

where U, V, U_S, V_S are components of the mean current velocity and Stokes drift along the horizontal axes x and y, respectively.

Experimental data

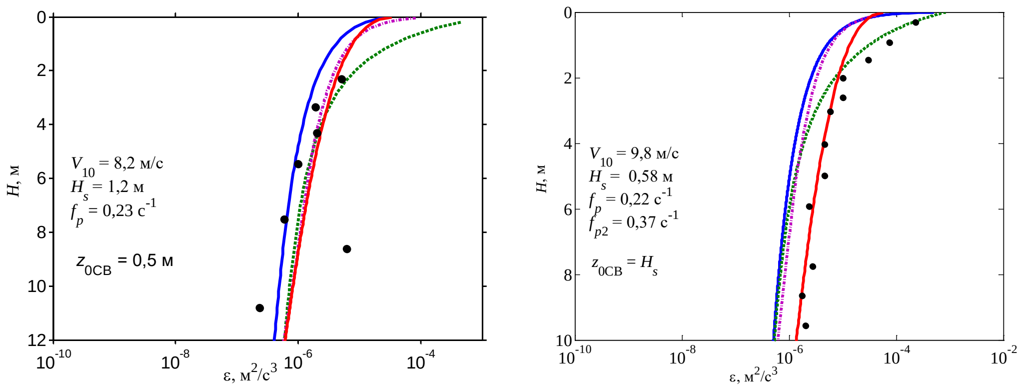
For a number of years, the staff of the Turbulence Department of Marine Hydrophysical Institute of RAS (MHI) have been conducting experimental studies of the turbulent exchange processes in the near-surface layer of the sea on the stationary oceanographic platform of the MHI Black Sea hydrophysical sub-satellite polygon. The main instrument during operational observations is the *Sigma-1* multifunctional measuring complex (positional version) [44]. Another complex is *Vostok-M* providing information on the module and direction of the main current velocity, as well as on the mean temperature and electrical conductivity values. In the process of measurements, the complexes are synchronously positioned on the same horizon with an exposure intervalsufficient for statistical measurement provision (10–20 min). A number of other hydrophysical characteristics necessary for the analysis were kindly provided by the employees of the Remote Sensing

Methods and Shelf Hydrophysics Departments of MHI. Physical parameters were recorded by their observing systems deployed on an oceanographic platform on a permanent basis or during the period of our experiments. The specialized experiments were carried out jointly with A.M. Obukhov Institute of Atmospheric Physics RAS, due to which the set of measured meteorological and hydrophysical characteristics was significantly expanded [45, 46]. Thus, the set of simultaneously measured hydrometeorological parameters was quite complete, which permitted adequate parameterization of the characteristics under study and verification of the theoretical models.

To characterize the turbulence intensity, the values of the dissipation rate of turbulent energy ε are usually used, which we calculated from the measurements of the three components of the velocity pulsations by the *Sigma-1* complex and the mean current velocity at a given horizon. The dissipation rate profile determined from the experimental data was compared with the calculations obtained using various models. The method for calculating of ε is described in sufficient detail in [10].

The verification of the turbulent exchange models described above for the near-surface layer of the sea based on experimental data collected over several years permits to make some conclusions.

The results of calculations using the models from [8–10] at wind speeds of 5–9 m/s were in satisfactory agreement with the measured data. Under stronger winds and in stormy conditions, the multiscale model of A.M. Chukharev [10] shows the best agreement between the calculation results and experimental data in comparison with other models. Fig. 2 shows examples of calculations for various models and the corresponding experimental data.



F i g. 2. Comparison of the model (lines) and experimental (dots) dependences of the turbulent energy dissipation rate ε on depth at different wind speeds H [10, p. 483–484]. On the left are the hydrometeorological parameters at which the calculations were performed: V_{10} – wind speed at the altitude 10 m; H_s – height of significant waves; f_p – frequency of the wave spectral peak; z_{0CB} – roughness parameter in the Craig and Banner model [8]. Represented are the calculations by the following models: for wall turbulence (blue curve); the Craig and Banner model [8] (green dash line); the Kudryavtsev V.N. et al. model (purple dotted line), the A.M. Chukharev multiscale model [10] (red line)

Nevertheless, there is a large array of experimental data, when compared with which none of the models gives a satisfactory agreement with the distribution of the dissipation rate over depth. Theoretical calculations with calm wind and insignificant waves show significantly lower values: discrepancies can reach 2–3 orders of magnitude.

Another group of data can be attributed to hydrometeorological situations that are not taken into account in the models, but quite often occur in real conditions: this is the presence of several systems of waves and swell, as well as different directions (primarily head-on) of wind, waves and currents. Separately, the Langmuir circulations presence can be noted. In these cases, the models can also give underestimated values of the dissipation rate. For obvious reasons, unsteady waves and/or unsteady turbulence are factors that are not taken into account in the described stationary models, inapplicable for these cases. With this consideration in mind, the objectivity of the considered models was estimated for conditions close to stationary and classical (stable wind, wind close in direction, current and waves).

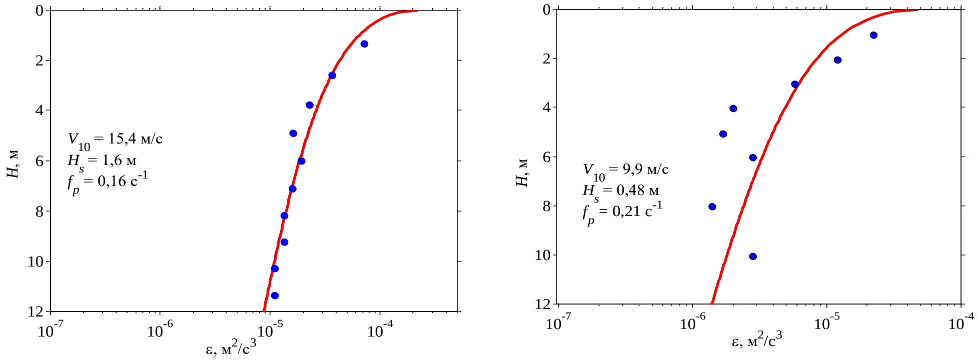
Thus, a comparative analysis of field measurements and theoretical calculations showed that, despite the quite satisfactory agreement in many cases between experimental and model data at moderate wind speeds, the considered models cannot always serve as a reliable tool for assessing the turbulence intensity near the sea surface.

Calculation of the relative contribution of turbulence generation mechanisms in various hydrometeorological conditions

Since among the models noted here, various turbulence sources are most fully represented in the multiscale model [10] and the agreement with experimental data on the set of considered cases was most often observed for the results of calculations using this model, the main analysis of the calculations was carried out using it.

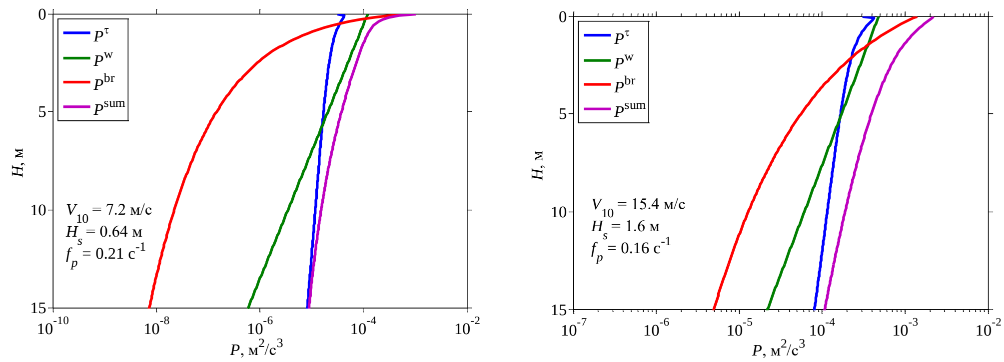
The multiscale model gives possibility to calculate the turbulence energy and dissipation rate for each turbulence source in the appropriate range of scales and estimate their absolute and relative contributions at various depths. The evaluation procedure was as follows. The experimental data obtained in various hydrometeorological situations were compared with the results of model calculations, and the selection of the constants achieved their best agreement, while the total effect of all generation mechanisms existing under these conditions was assumed. The energy inflow from the breaking waves was taken into account in the model according to the input parameters, principally, according to the wind speed.

Fig. 3 shows examples of correspondence between model [10] and experimental values of the dissipation rate of turbulent energy in various hydrometeorological conditions.



F i g. 3. Dependence of the turbulent energy dissipation rate on depth under different hydrometeorological conditions. Designations are the same as in Fig. 2

Contribution of individual turbulence generation mechanisms was calculated using the formulas given above (Fig. 4). Fig. 4 shows the data obtained under moderate and strong winds. At weak winds, as already mentioned, the results of calculations using the model significantly differed from the experimental data, so their reliable analysis is very difficult. The relative contribution of each of the generation mechanisms depends on hydrometeorological conditions and varies with depth. Contribution from surface wave breakings (red curve in Fig. 4) appears at wind speeds exceeding 5 m/s. A significant role in the turbulence generation by waves is also played by their degree of development, height and steepness. As can be clearly seen from the figure, in different conditions and at different depths one or another mechanism can dominate, therefore, even with a developed storm, it is important to take into account all the mechanisms of turbulence generation.



F i g. 4. Contribution of the main mechanisms of turbulence generation in different hydrometeorological conditions. Designations are the same as in Fig. 1 and 2

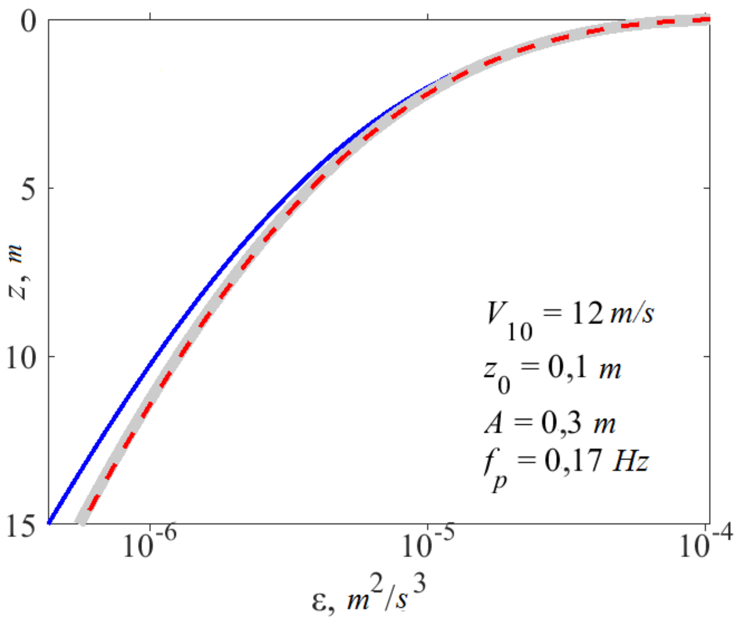
In comparison with the previously proposed model [10], its new improved version adds the ability to take into account the Stokes drift and Langmuir circulations influence. Stokes drift is accounted for as an increase in the total velocity shear:

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

Calculation of the turbulence generation due to the Langmuir circulations operation was carried out both by relation (3), proposed in [33], and by the formulas proposed in [38–40]. Comparison of the previously proposed and modified model showed that the inclusion of the Stokes drift in the model slightly improves the objectivity of the model calculations, while the addition of the Langmuir circulations as a turbulence source in accordance with formula (3) has almost no effect on the results. Fig. 5 shows the calculations for the multiscale model for all the cases indicated.

An alternative method for Langmuir circulations contribution estimating in accordance with expression (2) through an increase in the vertical transfer of kinetic energy depending on the Langmuir number in the multiscale model [10] was used to calculate the generation of turbulence by wave motions. In formula (1), instead of u_*, the value $\sqrt{< w'^2 >}$ determined through the relation [40] was used

$$\frac{< w'^2 >}{u_*^2} = 0{,}64[1 + 0{,}098 \mathrm{La}_t^{-2}] \cdot \qquad (4)$$



F i g 5. The rate of turbulent energy dissipation ε calculated by ratio (1): with no regard for the Stokes drift and the Langmuir circulations (blue curve); with the regard for the Stokes drift (grey curve); with the regard for the Stokes drift and Langmuir circulations (red dash line)

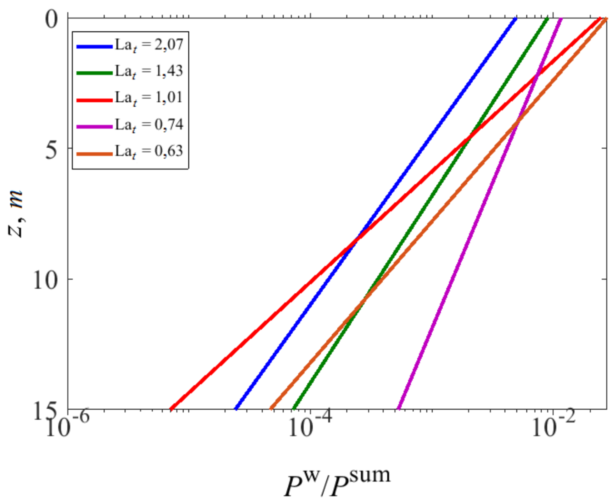
Verification of the dependence somewhat different from relation (4) proposed in [40] based on LES modeling was also carried out:

$$\frac{< w'^2 >}{u_*^2} = \begin{cases} 0{,}398 + 0{,}48\mathrm{La}_{\mathrm{SL}}^{-4/3}, & \mathrm{La}_{\mathrm{SL}} \le 1 \\ 0{,}64 + 3{,}50\exp(-2{,}69\mathrm{La}_{\mathrm{SL}}), & \mathrm{La}_{\mathrm{SL}} > 1 \end{cases}. \quad (5)$$

In contrast to formula (4), here, as a parameter, the authors used the Langmuir number $\mathrm{La}_{\mathrm{SL}}$ calculated from the Stokes drift averaged over 1/5 of the upper part of the mixed layer. Calculation by formula (4) demonstrates a weak Langmuir circulations influence on the turbulence intensity, while dependence (5) shows somewhat better agreement with observations: at Langmuir numbers greater than 1, the Langmuir circulations contribution is insignificant, and at $\mathrm{La}_t < 1$ it can reach 15 % (at $\mathrm{La}_t = 0{,}63$).

Fig. 6 shows the results of calculations (with real hydrometeorological conditions) of the ratio of the wave motions generation rate by to the total rate of turbulent energy generation $P^{\mathrm{w}}/P^{\mathrm{sum}}$ taking into account dependence (5) at different Langmuir numbers.

According to Fig. 6, there is a tendency towards an increase in the relative contribution of P^{w} (due to an increase in the vertical rate of kinetic energy transfer) to the total turbulence generation. Additional factors affecting this ratio are the amplitude and frequency of the waves: at higher amplitudes, the contribution of wave turbulence manifests at greater depths. In a certain sense, a decrease in the Langmuir number characterizes an increase in the steepness of surface waves, i.e., an increase in nonlinear effects in wave motions.



F i g. 6. Change of the relative contribution of turbulence generation by surface waves as a function of the Langmuir turbulent number

Conclusion

In the spirit of the above, it can be stated that at this stage of the study of the problem of turbulent exchange parameterization in the upper mixed layer of the sea, a number of unsolved problems remain. Unfortunately, there is no adequate theoretical description of the complex interactions of various dynamic processes under the sea surface. Drift current, wave motions, wave breaking, Stokes drift and Langmuir circulations are sources of turbulence and make a certain contribution to vertical mixing.

The first three of the listed sources make the greatest contribution to the upper layer turbulization, but taking into account only these generation mechanisms in the models permits to describe the experimental results not always successfully.

The development of a multiscale turbulence model [10], described in the present study, allows including the influence of the Stokes drift and Langmuir circulations in theoretical calculations. Calculations using an improved model with real input parameters obtained in measurements (wind speed, height and frequency of the spectral peak of waves) showed that taking into account the Stokes drift adds to the total rate of turbulent energy dissipation from 2 to 17 % to the total over a 30 m layer. At the same time the Langmuir circulations influence, parameterized in accordance with formula (3), is practically unnoticeable (less than 1 %). Another proposed method for taking into account Langmuir circulations, such as an increase in the vertical transfer of kinetic energy depending on the turbulent Langmuir number, according to formula (5), gives in the calculations a more significant contribution to the total turbulization of the layer: up to 15 % at $\mathrm{La}_t < 1$.

The obtained results, unfortunately, do not give an unambiguous picture of the Langmuir circulations influence on the turbulent exchange in the near-surface layer due to the absence of their generally accepted parameterization. Possibly, relations (4) and (5) are not completely universal and require more careful experimental verification under specific regional hydrometeorological conditions.

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