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Abstract

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Results of Direct Determination of the Intensity of Deep Turbulent Exchange in the Atlantic Ocean

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A direct method for determining the characteristics of turbulence in the ocean, based on statistical processing of records of fluctuations of the horizontal and vertical components of current velocity, temperature, and salinity, obtained by means of turbulimeters ([1–4]), proved to be very effective and made it possible for the first time to establish a number of features of exchange under different hydrological conditions. The studies carried out ([5–8]), however, covered only the surface layer of the ocean. Meanwhile, direct investigations of turbulence not only in the surface, but also in the deep and near-bottom layers of the ocean, are of great interest. The transition to deep-water investigations required fundamental changes in the apparatus developed earlier; first of all, this was caused by abandoning the cable connection of the instrument with the ship and introducing complete automation of the measurement process. In 1959 we built the first model, and in 1961 a second, more advanced model, of a deep-water autonomous turbulimeter, making it possible to carry out automatic recording of fluctuations of the components of current velocity and water temperature, as well as of the mean current velocity.

The measurement circuit of the deep-water autonomous turbulimeter is switched on by an automatic control unit according to a prescribed program. The apparatus is powered by small storage batteries and anode batteries. All units of the measuring apparatus are placed in a single container designed for immersion to 2000 m. Fluctuations of current velocity are measured by a platinum thermohydrometer of alternating current with indirect heating. To measure temperature fluctuations the same sensor is used without heating. The linear dimensions of the sensitive element of the sensor are of the order of ~ 1 cm. The time constant of the apparatus does not exceed 0.02 sec. The mean current velocity is measured by a rotor with photo readout. The measured quantities are recorded on 35-mm motion-picture film. For convenience in decoding the pulsation curves, recording on color film in four different colors is used.

In 1959–1961 the new instrument was tested in the Black Sea, both in a non-autonomous version and in an autonomous deployment, at depths down to 1000 m. In November 1961, using the deep-water autonomous turbulimeter, the first

Fig. 1. Longitudinal correlation function of the velocity field. Observation time $T_n = 300$ sec.

Figure 1: Fig. 1. Longitudinal correlation function of the velocity field. Observation time $T_n = 300$ sec.

studies of deep turbulent exchange in the Atlantic Ocean were carried out during the 11th cruise of the research vessel *Mikhail Lomonosov*. In all, 3 series of measurements were carried out in the Gulf Stream region. In each series of observations, lasting 3–4 hours, the turbulimeter, operating automatically and switching on periodically, carried out continuous recording of fluctuations of current velocity. The oscillographic records obtained were statistically processed on a correlometer. As a result of selective processing of the observational materials, the principal characteristics of turbulence in the ocean at a depth of 500 meters were found for the first time.

Main Results of the Investigations

Horizontal turbulent exchange. As is known, turbulent diffusion in the ocean takes place over a very broad spectrum of scales of velocity fluctuations, so that, with the actual duration of continuous observation, only some kind of

region of this spectrum, the width of which depends on the duration of the measurement T_n or on the observational scale L_n.

The duration of the continuous recording of pulsations of the horizontal component of the velocity $u(t)$ of the flow relative to the instrument moving in the turbulent medium was, in our measurements, determined by the time t_n, on average equal to 75 sec, between two automatic balances of the "zero" of the measuring circuit when the mean level of the velocity fluctuations drifted owing to the influence of large-scale eddies. From t_n it is easy to pass to the spatial scales of turbulence $L_n = Vt_n$.

Fig. 1. Longitudinal correlation function of the velocity field. Observation time $T_n = 300$ sec.

At an instrument velocity relative to the water $V \simeq 40$ cm/sec, for L_n we obtain a value of the order of 30 m.

The mean velocity $\bar{u}$ in the region of observations, according to measurements with recording current meters installed on an anchored buoy, was about 10 cm/sec. Assuming that the whole pattern of turbulent fluctuations is transported by the existing current, the time of passage of a region of extent $L_n \simeq 3 \cdot 10^3$ cm is measured by a quantity T_n of the order of 300 sec, which may be regarded as the temporal scale of the observations.

The structure of the turbulent velocity field is determined by the spatial correlation function $R_r(r)$, where r, on the basis of the concept of "frozen turbulence," is related to the "lag" t of the passage of velocity fluctuations through the sensor: $r \simeq Vt$. Using the same concept, from the spatial correlation function $R_{\mathrm{r}}(r)$ one may pass to the Eulerian correlation function $R_{\mathrm{r}}(\tau)$, characterizing the temporal structure of turbulence in the existing field of mean velocities $\bar{u}$. Then $\tau \simeq r/\bar{u}$.

In the Lagrangian method of describing turbulent diffusion, the coefficient of horizontal diffusion K_{r}, according to (9), is expressed through the Lagrangian correlation function $R^*_{\mathrm{r}}(\xi)$, and the mean square of the pulsations of the horizontal component of the velocity of a fixed diffusing particle $\bar{u}^{*2}$ is determined as follows:

$$K_{\mathrm{r}} = \bar{u}^{*2} \int_0^\infty R^*_{\mathrm{r}}(\xi)\, d\xi. \tag{1}$$

The unknown quantity of the Lagrangian turbulence scale in (1)

$$\xi_{0\mathrm{r}} = \int_0^\infty R^*_{\mathrm{r}}(\xi)\, d\xi$$

can be related to the turbulence scale in the Eulerian representation

$$\tau_{0\mathrm{r}} = \int_0^\infty R_{\mathrm{r}}(\tau)\, d\tau$$

by the approximate relation $\xi_{0\mathrm{r}} \simeq \gamma\tau_{0\mathrm{r}}$.

$\tau_{0\mathrm{r}}$ can easily be found from the experimental correlation

function $R_\Gamma(\tau)$ of the fluctuations of the current velocity $u(t)$. The form of such a function is shown in Fig. 1. Integrating $R_\Gamma(t)$, we find $\tau_{0\Gamma} \simeq 12$ sec. The proportionality coefficient γ is related to the turbulence intensity $\sigma_u = (\overline{u^2})^{1/2}/\overline{u}$ by the theoretical relation $\gamma = 1.12/\sigma_u + 1$.

As a result of the investigations carried out, experimental values of σ_u were obtained; they are given in Table 1. Different values of σ_u correspond to different portions of the oscillogram. The same table gives the values of the Lagrangian turbulence scales $\zeta_{0\Gamma}$. Substituting $\zeta_{0\Gamma}$ into (1), we approximately estimate K_Γ (here the quantity $\overline{u^{*2}}$ entering into (1), for a sufficiently long measurement, may simply be replaced by the mean square of the component of the velocity fluctuations in the flow, $\overline{u^2}$). On the average, for the coefficient of horizontal turbulent diffusion at a depth of 500 m, the value $K_\Gamma \simeq 200$ cm^2/sec was obtained.

Table 1

$(\overline{u^2})_\tau^{1/2}$, $\frac{\text{cm}}{\text{sec}}$	$(\overline{u^2})_\tau$, $\left(\frac{\text{cm}}{\text{sec}}\right)^2$	σ_u, %	γ	$\zeta_{0\Gamma}$, sec	K_Γ, $\frac{\widetilde{\text{cm}^2}}{\text{sec}}$
1.38	1.90	13.8	9	108	200
0.69	0.48	6.9	17	204	100
1.50	2.25	15.0	9	108	240
1.66	2.76	16.6	8	96	270
Average 1.30	1.85	13.0	11	~ 130	~ 200

As is known, the magnitude of the diffusion coefficient depends on the scale of the phenomenon: $K(L) = CL^{4/3}$. In the atmosphere this dependence was first observed experimentally by Richardson, was theoretically substantiated by A. M. Obukhov, and was confirmed by numerous measurements of horizontal diffusion over wide ranges of variation of L. Similar studies in the surface layer of the ocean have been carried out by many authors ([11–15]) and others. It follows from these studies that the 4/3 law for horizontal diffusion in the surface layer of the ocean is justified for L from tens of centimeters to several kilometers. In this case the average value obtained for C was $C = 0.01$ cm$^{2/3}$/sec. For the deep layers of the ocean, such studies had not been carried out until now.

The approximate estimates of the turbulence characteristics that we have made correspond to the scale of the phenomenon $L \simeq 3 \cdot 10^3$ cm.

Extension of the results obtained to larger-scale processes without special verification of the 4/3 law under our conditions is, strictly speaking, not justified. However, there are grounds for assuming that in some range of scales $L > L$ the 4/3 law also holds for the deep layers of the ocean. If we use the relation $K(L) = CL^{4/3}$ and substitute here the numerical values found, $K_\Gamma(L) \simeq 200$ cm^2/sec and $L \simeq 300$ cm, then it is possible to estimate the coefficient C for deep turbulent diffusion as $C \simeq 4.6 \cdot 10^{-3}$ cm$^{2/3}$/sec. Thus, at depths on the order of 500 m, assuming the validity of the 4/3 law, the numerical value of C is somewhat smaller than in the surface layer.

Vertical turbulent exchange

The coefficient of vertical turbulent diffusion $K_\text{v}(L)$ is determined by an expression analogous to (1), through the vertical component of the particle-velocity fluctuations W^* and the Lagrangian turbulence scale $\zeta_{0\text{v}}$, corresponding to the vertical component of the turbulent motion:

$$K_\text{v}(L) = \overline{w^{*2}} \int_0^\infty R_\text{v}^*(\xi)\, d\xi. \tag{2}$$

The quantity $\overline{w^{*2}}$ (analogously to the quantity $\overline{u^{*2}}$) may be taken as coinciding with the value $\overline{w^2}$, found from measurements of the pulsation component of velocity in the oncoming flow.

The Lagrangian scale of turbulence

$$\zeta_{0\text{v}} = \int_0^\infty R_\text{v}^*(\zeta)\, d\zeta,$$

corresponding to the vertical component, can be estimated on the basis of certain general considerations concerning the turbulent structure of the velocity field.

It is evident that the dimensions of the largest "eddies" carrying out diffusion cannot exceed the spatial scale of observation $L_\text{n} \sim T_\text{n}$. It is well known that, as the observation time is increased, the dimensions of the effective "eddies" λ grow in proportion to T_n. This dependence in the near-ground layer of the atmosphere for the horizontal scales λ_g holds over wide limits ([16,17]). The vertical dimensions of the largest "eddies" λ_v, participating in the diffusion process, are limited in the atmosphere by the height of observation. In the ocean λ_v is correspondingly limited by the depth, and also by the inhomogeneity of the density field in the vertical; consequently, the limits of growth of λ_v in general, as the observation scale is increased, are not as wide as in the case of horizontal diffusion in the ocean.

Thus, one may conclude that if, with an increase in the observation scale, the ratio $\lambda_\text{g}/\lambda_\text{v}$ increases ($\lambda_\text{g}/\lambda_\text{v} > 1$), then as L_n is decreased it approaches unity. In our case, at a depth of 500 m, i.e., far from boundary surfaces, with a relatively small observation scale $L_\text{n} \sim 30$ m, the turbulent motion may, to a known approximation, be regarded as locally isotropic.

The Lagrangian scale of turbulence entering relations (1) and (2), respectively, for horizontal and vertical diffusion, $\zeta_{0\text{g}}$ and $\zeta_{0\text{v}}$, is close to the concept of the "lifetime" of the maximum effective "eddy" ([18,19]) and is related to the horizontal λ_g and vertical λ_v dimensions of the maximum "eddies" participating in diffusion by the dependences: $\lambda_\text{g} \simeq \zeta_{0\text{g}}(\overline{u^2})^{1/2}$ and $\lambda_\text{v} \simeq \zeta_{0\text{v}}(\overline{w^2})^{1/2}$. Consequently, if one assumes that the turbulent motion within the observation scale L_n is isotropic, i.e. $\lambda_\text{g} \simeq \lambda_\text{v}$ and $(\overline{u^2})^{1/2} \simeq (\overline{w^2})^{1/2}$, then the Lagrangian scale of turbulence for horizontal and vertical diffusion will be characterized by a quantity of the same order. Using, for an approximate estimate of the coefficient of vertical exchange, our data on the horizontal structure of the velocity field, we naturally obtain for $K_\text{v}(L_\text{n})$ the same value, ~ 200 cm^2/sec. The value found is, in order of magnitude, close to the values of K_v obtained by us earlier by indirect methods ([20]).

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Note: Figure translations are in progress. See original paper for figures.