Spectral Characteristics of Small-Scale Fluctuations of Hydrophysical Fields in the Upper Layer of the Ocean

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ABSTRACT

In the P. P. Shirshov Institute of Oceanology of the USSR Academy of Sciences, instrumentation has been developed for the measurement of the fluctuations of the hydrophysical fields in the ocean in the frequency band from a fraction to a few hundred hertz under conditions of towing as well as sounding on station. Research was conducted on a number of the polygons in the Atlantic, Pacific and Indian Oceans with typical hydrometeorological conditions. A set of the statistical characteristics of the micropulsations of the hydrophysical fields in the ocean is calculated, including the spectral densities $E_1(k)$, where k is the wavenumber. The level of the spectral densities $E_1(k)$ and their slope (in logarithmic coordinates) are rather variable. For single cases the functions $E_1(k)$ could be approximated by the $k^{-5/3}$ law of locally isotropic turbulence. In the small-scale part of the spectrum, a quick decrease of the values $E_1(k)$ is often observed, evidently caused by the influence of molecular viscosity (or thermal conductivity). In some cases the spectral curves have a shape typical of non-developed turbulence at comparably small values of the Reynolds numbers (10^4–10^5). In a number of cases, however, over the range of k studied the spectral densities of the current velocity pulsations have a steeper slope than $-5/3$ which might be explained by the influence of the buoyancy forces on the turbulent structure.

During recent years, the Shirshov Institute of Oceanology of the USSR Academy of Sciences has carried out extensive studies of small-scale fluctuations of hydrophysical fields in the ocean (Ozmidov, 1973). For this purpose special complex metering systems have been constructed. Velocity fluctuations were measured by thermo-anemometric and electromagnetic sensors, temperature fluctuations by platinum-film resistance thermometers, electro-conductivity by contact sensors of different designs (Vorobjev *et al.*, 1973, 1974; Vorobjev and Palevich, 1974). In these studies, the frequency band extended from a fraction to a few hundred hertz. The linear sizes of sensitive elements

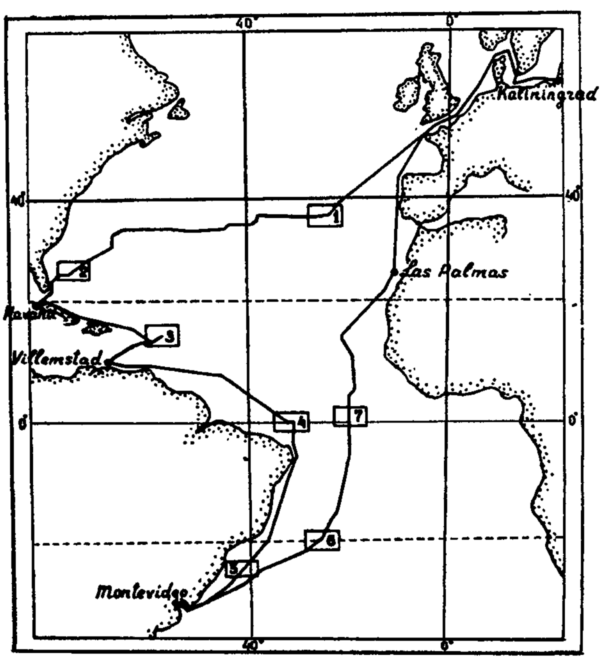

FIG. 1. Positions of polygons during cruise 9 of *Akademik Kurchatov*.

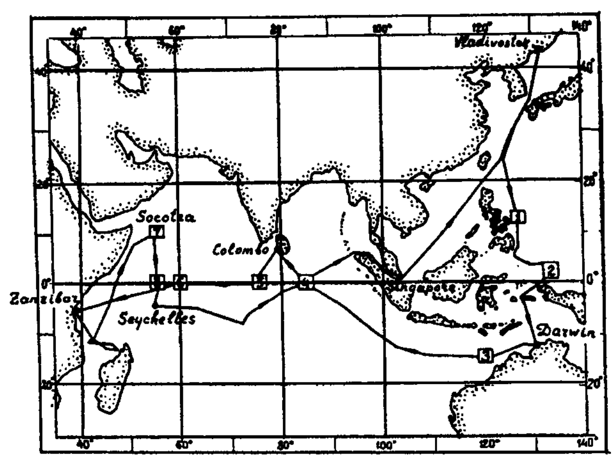

FIG. 2. Positions of polygons during cruise 7 of *Dmitry Mendeleev*.

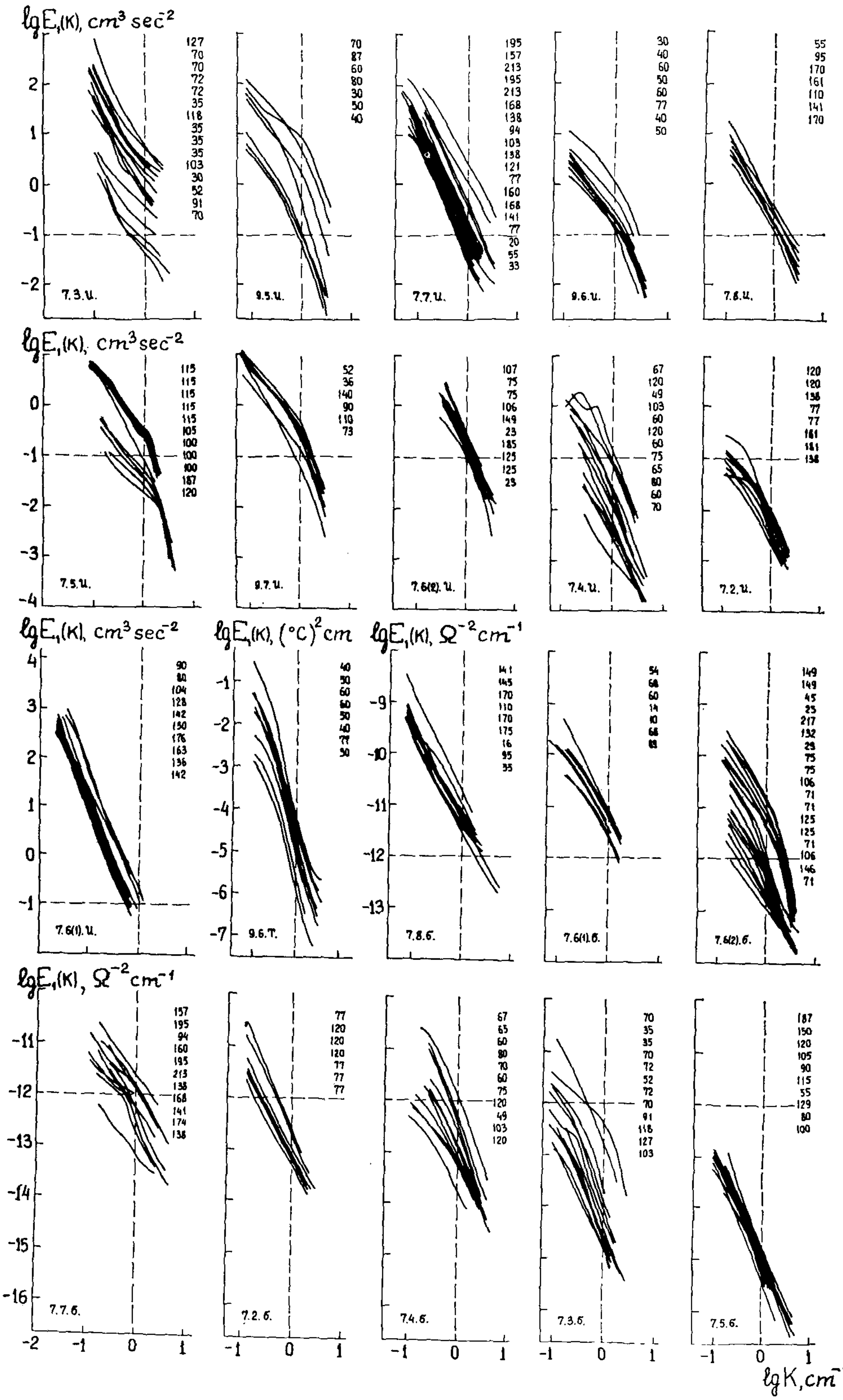

FIG. 3. Summary of averaged turbulence spectra in upper layer of ocean. See the explanation of notation in the text.

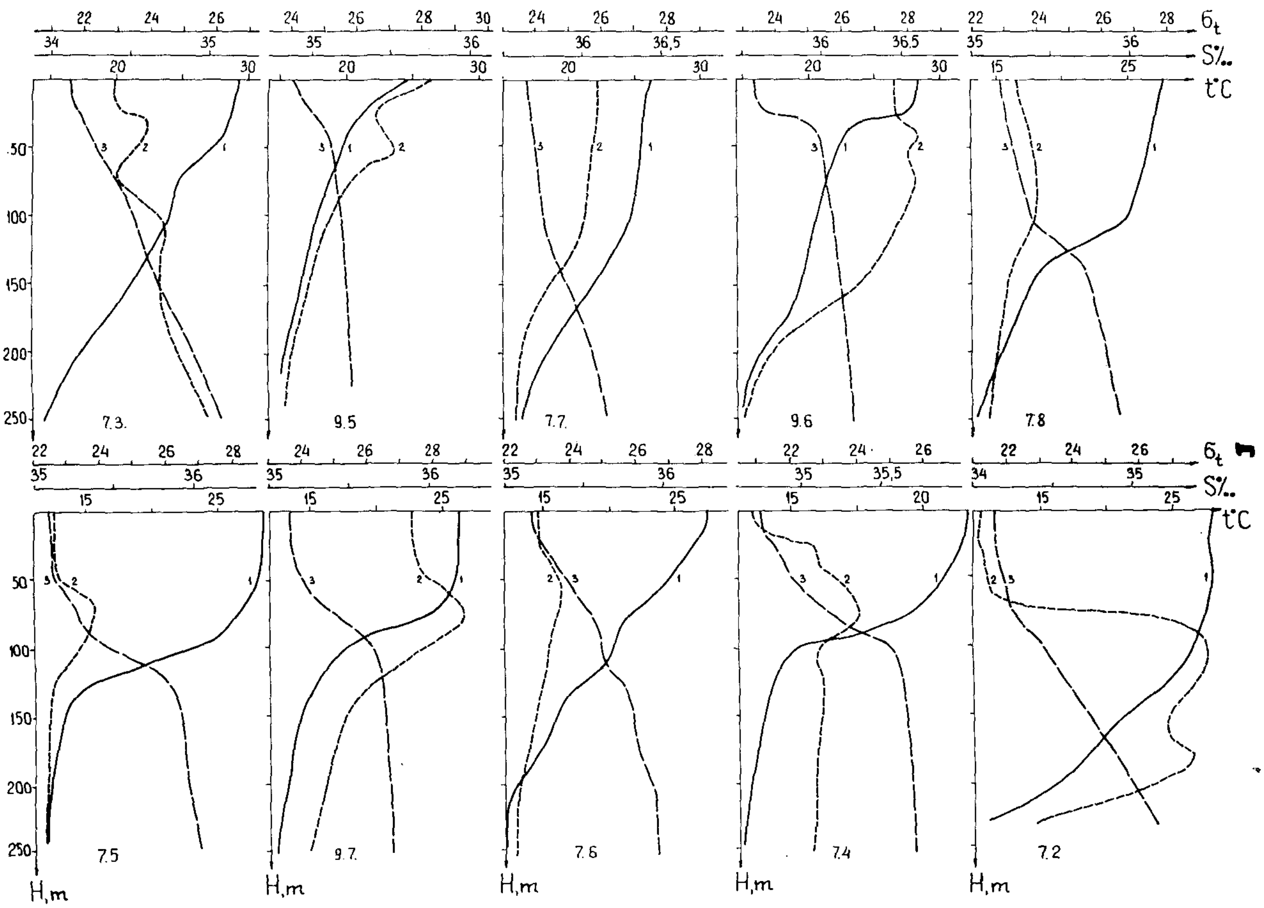

FIG. 4. Vertical distribution of temperature (1), salinity (2) and σ_t density (3) in the various polygons.

of sensors were about several millimeters. Instruments were adapted for towing behind ships as well as for vertical probing from drifting vessels. High-frequency signals were recorded in analogue form and analyzed on ships' computers (Belyaev, 1973).

Figs. 1 and 2 show the routes of the research vessels *Akademik Kurchatov* and *Dmitry Mendeleev* during cruise 9 and 7, respectively. Because of difficulties often encountered with measurements during rough weather, measurements were performed mainly in tropical regions: on polygons 5–7 of cruise 9 of *Akademik Kurchatov* in January and February, 1971, in the Atlantic Ocean, and on polygons 2–8 of cruise 7 of *Dmitry Mendeleev* in January to March, 1972, in the Pacific and Indian Oceans.

All measurements were performed by means of turbulimeters towed behind moving ships (Paka, 1972). Radian frequencies ω have been transformed into wavenumbers by the Taylor hypothesis $k=\omega/V$, where V is the speed of the sensor relative to the water.

Fig. 3 presents on bi-logarithmic scales one-dimensional averaged spectral densities $E_1(k)$ of small-scale fluctuations in the wavenumber range $k\approx 10^{-1}$ to 10^1 cm^{-1}, of longitudinal velocity u, temperature T, and electro-conductivity σ at different depths in the upper 200 m of the ocean. Two numbers and a letter in the left-hand corner of each graph in Fig. 3 indicate the cruise number, the polygon number and the measured quantity; thus 7.6. u denotes velocity u of polygon 6 of cruise 7. Depths of sensor deployment are given in meters in the right-hand upper corners of the graphs in the sequence of disposition of left-hand ends of spectral curves from top to bottom. Vertical broken lines correspond to the wavenumber $k_0=1$ cm^{-1}, horizontal lines to the standard levels of spectral density 10^{-1} cm^3 s^{-2} and 10^{-12} Ω^{-2} cm^{-1} for u and σ, respectively. Note that on polygon 7.6 the quantities u and σ were measured twice by means of different sensors with like meteorological characteristics. The measurements in this case were separated by approximately 24 h, hence their results are presented on two different graphs.

Hydrographic conditions on the different polygons are illustrated by Fig. 4, which, according to standard hydrographical measurements, presents vertical profiles of temperature (t), salinity (S) and density (σ_t) for all these polygons. Cruise number and polygon number are indicated for each set of curves in the same sequence as in Fig. 3.

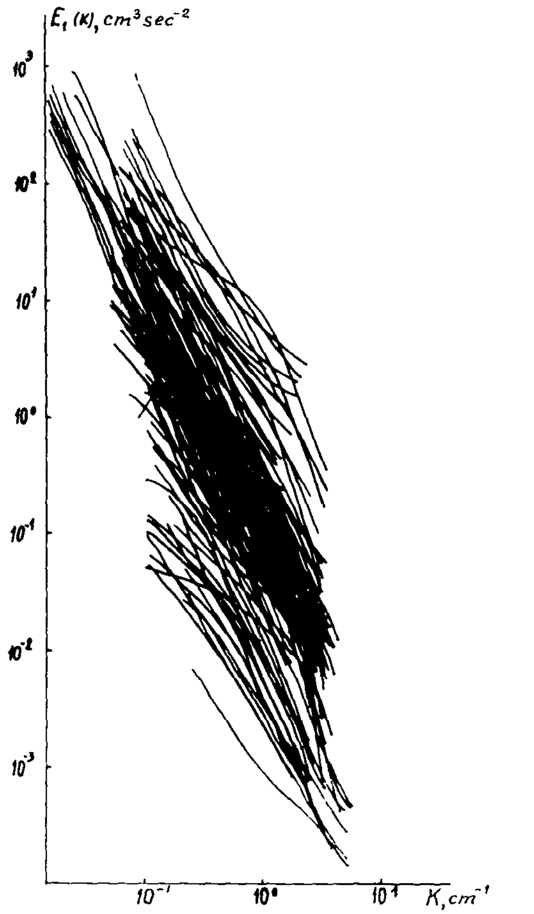

FIG. 5. Averaged curves of one-dimensional spectra of velocity fluctuations in the ocean.

In the first place, Fig. 3 demonstrates the great variety of turbulent regimes in the upper layer of the ocean. For example, at wavenumber $k_0 = 1$ cm^{-1}, magnitudes of spectral densities of u vary from 10^1 cm^3 s^{-2} at depths of 127 and 70 m on polygon 7.3 and depths of 70 and 87 m on polygon 9.5 to 10^{-3} cm^3 s^{-2} at certain depths on polygons 7.2 and 7.4. Magnitudes of spectral densities of σ at the same wavenumber vary even over five orders of magnitude from 10^{-11} Ω^{-2} cm^{-1} on polygon 7.8 to 10^{-16} Ω^{-2} cm^{-1} on polygon 7.5. On certain polygons, the turbulence is approximately homogeneous with depth (for example, 7.8.u, 7.6.u, 7.2.u, 7.8.σ, 7.2.σ and 7.5.σ). On other polygons, its level varies significantly with depth (for example, 7.3.u, 9.5.u, 7.4.u, 7.4.σ and 7.3.σ), and variations span two decades. At the same time, turbulence levels do not remain constant with depth; instead, layers with weak and strong turbulence alternate. Obviously, this phenomenon is related to the microstructure of the stratification of the thermodynamical parameters of water and of the velocity of flow (Belyaev, *et al.*, 1974). Mean rates of decrease of spectral densities and the shape of turbulence spectra are seen to very widely.

Figs. 5 and 6 summarize all 123 spectral curves for the velocity u and 85 spectral curves for the electroconductivity σ, respectively. The character of the distributions of $E_1(k)$ for u and σ fluctuations are seen to differ somewhat. Fig. 7 presents histograms of $\log E_1(k)$ for u and σ, using steps of 0.5. For the series of $\log E_1(k)$ Table 1 gives the mean value m, the variance D, the standard deviation $s = D^{\frac{1}{2}}$, skewness A, and $E = K - 3$, where K is the kurtosis.

The closeness of the empirical distribution functions to the normal distribution has been evaluated using Kolmogorov's criterion (see, e.g., Schigolev, 1969). For this purpose, the parameter $\lambda = \max|F^* - F| n^{\frac{1}{2}}$ has been computed, where F^* and F are the empirical and theoretical integral distribution functions, respec-

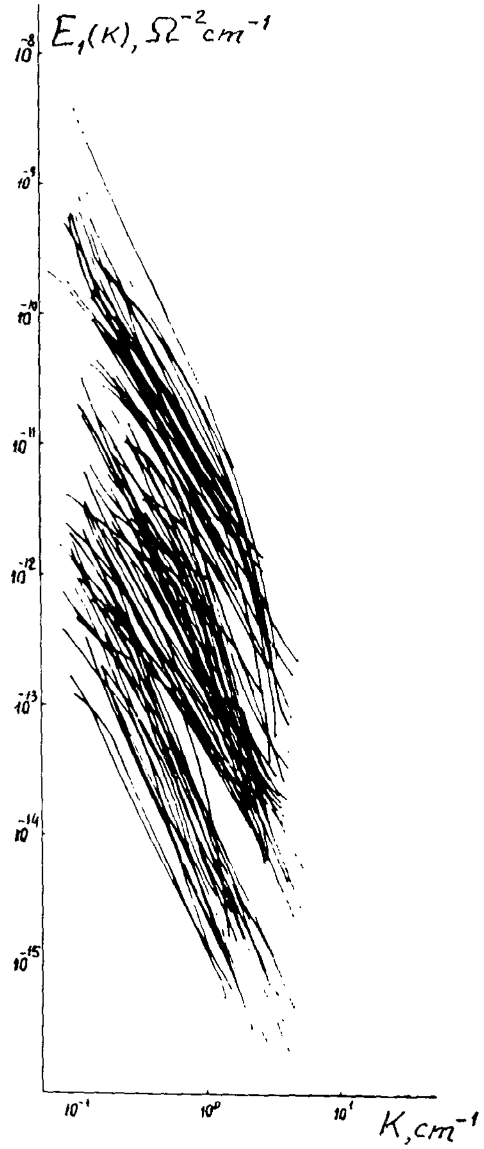

FIG. 6. Averaged curves of one-dimensional spectra of electroconductivity fluctuations in the ocean.

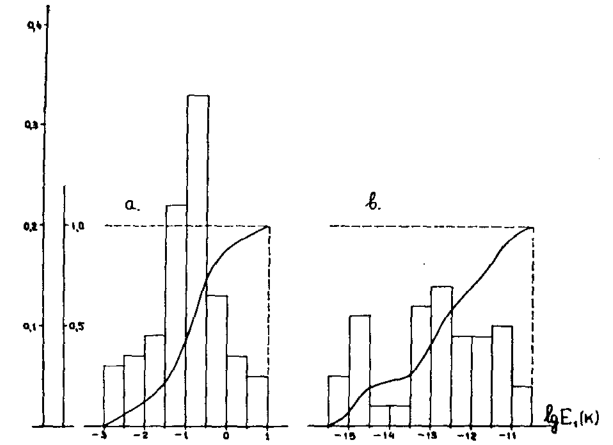

FIG. 7. Histograms and empirical probability distributions of $\log E_1(k)$ for fluctuations of velocity (a) and electro-conductivity (b) in the ocean at $k_0=1$ cm^{-1}. Left scale corresponds to histograms, right scale to probability distributions.

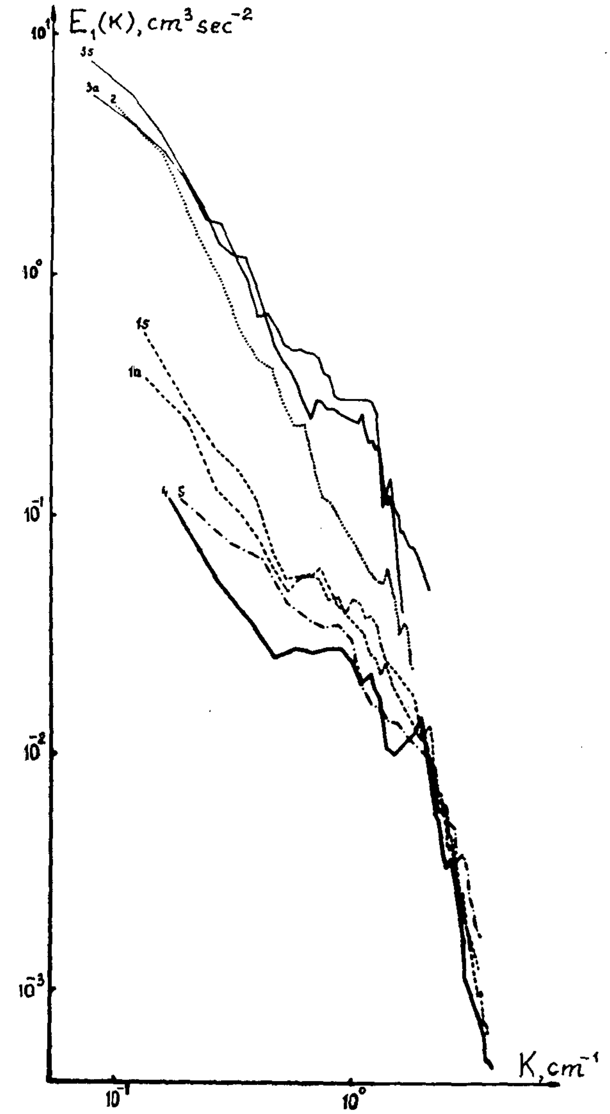

FIG. 8. Spectral densities of velocity fluctuations at polygon 7.5. Depths of measurement: 1 a, b, 100 m; 2, 105 m; 3 a, b, 115 m; 4, 120 m; 5, 187 m.

tively, and n is the number of observations. The probability that a hypothesis of $\log E_1(k)$ being a normal distribution is acceptable is thus 70% for u, but only 7% for σ. Hence it is seen that the empirical distribution function for $E_1(k)$ for the velocity fluctuations in the ocean over the wavenumber range under consideration is approximately log-normal. The σ fluctuations have a different distribution law. Such a difference in the distribution laws of spectral densities of u and σ is, apparently, conditioned by the fact that fluctuations of electro-conductivity are determined both by velocity fluctuations and by the value of the gradient of average electro-conductivity field. This value is in turn connected with the value of the density gradient which influences the turbulence regime in the ocean. Fluctuations of both temperature and salinity contribute to fluctuations of electro-conductivity. If, however, we regard fluctuations of temperature and salinity as proportional to the gradients of the respective average fields, it appears that the main contribution to the fluctuations of electro-conductivity in the upper layer of the ocean must be due to temperature fluctuations.

Obviously, these results relating to parameters of the spectral density distributions of velocity and electro-conductivity fluctuations are not representative for the world ocean under arbitrary hydrometeorological conditions. The experimental data available at present are not sufficient, and require extension.

TABLE 1. Parameters of the $\log E_1(k)$ series.

Signal	Parameters				
	m	D	s	A	E
μ	−0.94	0.64	0.80	0.09	0.01
σ	−12.87	1.72	1.31	−0.35	−0.92

A comparison of the turbulent regimes with the corresponding hydrographic conditions (see Figs. 3 and 4) shows that there exists a tendency for velocity fluctuations to decrease with increasing vertical water density gradients. The most intense velocity fluctuations were observed on polygons 7.3, 9.5 and 7.7 when the density was weakly stratified and discontinuities were absent. Evidently, in the presence of discontinuities, underlying water layers would be screened from downward vorticity transport, so that turbulence is only generated by shear instability of internal waves and microconvection, and bears a local character; the intensity of turbulence in this case must on the average be relatively small.

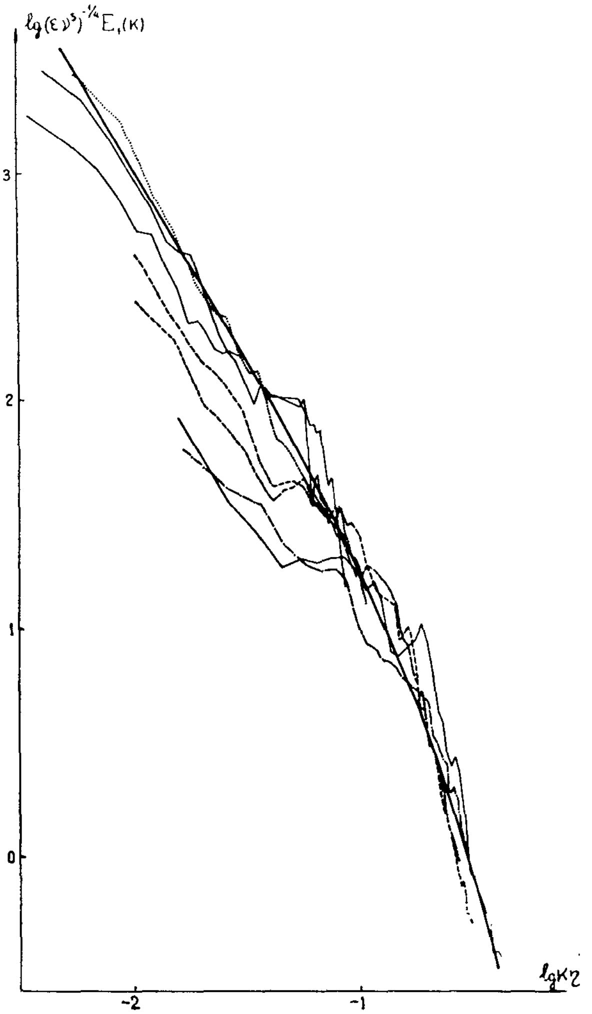

FIG. 9. Comparison of spectra 7.5.*u* with the universal curve of the inertial-viscous range.

In addition to $E_1(k)$, the spectral functions $kE_1(k)$ have also been computed. These functions characterize the energy distribution over the wavenumbers; in a number of cases, it exhibited a tendency toward saturation with decreasing k. Hence the Reynolds numbers for oceanic turbulence may not be very large, and as a consequence the inertial interval and universality of small-scale sections of the spectrum disappear.

In order to explain the shape of the spectral curves 7.5.*u* in Fig. 8, an attempt has been made to combine them with the universal curve of the inertial-viscous range, using a method proposed by Stewart and Grant (1962) by optimum visual coincidence between experimental points and the universal curve. In Fig. 9, these experimental spectra are represented in a satisfactory manner by the universal curve around the center of the wavenumber range under study; they deviate significantly from it for small wavenumbers. Their shape is typical for longitudinal spectra at not very large Reynolds numbers, obtained in laboratories where the Reynolds number was 10^4 to 4×10^4 (Gibson and Schwarz, 1963). The smallness of the Reynolds number in oceanic turbulence is also confirmed by the presence in the vertical density profiles of comparatively stationary layers which are separated from each other by thin layers with strong gradient properties.

The shape of the spectra 7.7.*u* in Fig. 10 may be due to the action of buoyancy forces. Following Monin (1962), the universal function of longitudinal velocity fluctuations in a stratified flow is readily obtained for comparison with the experimental data. Fig. 11 illustrates the combination of experimental curves with one-dimensional spectra of Monin's model, where $x=kL$ and $L=4\gamma^{-\frac{1}{2}}\alpha_0^{-\frac{3}{4}}L_*$, with γ the coefficient of proportionality in Heisenberg's hypothesis for the spectral form of the eddy viscosity, α_0 the ratio of the eddy coefficients for heat and momentum, and L_* Obukhov's buoyancy scale (Obukhov, 1959).

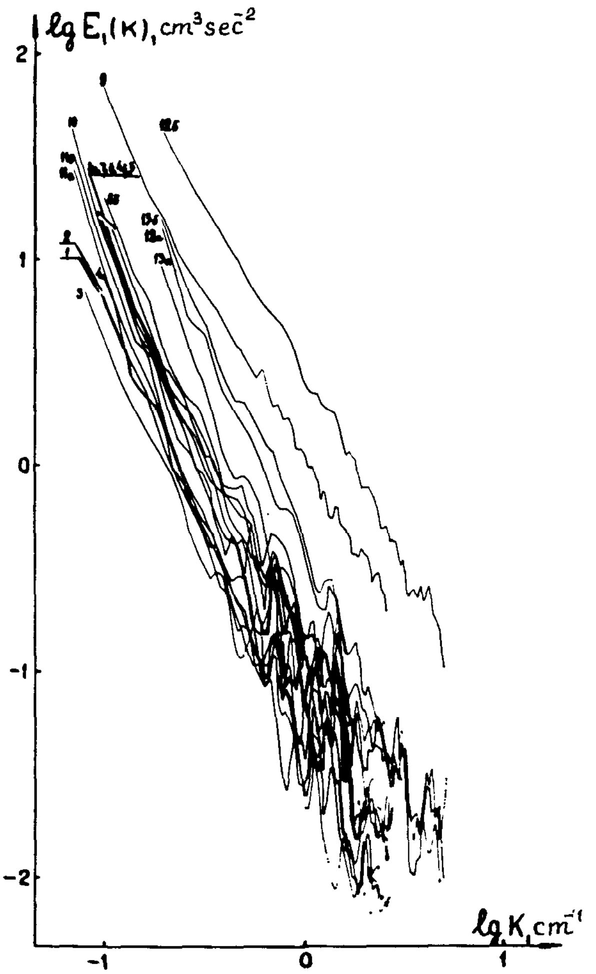

FIG. 10. Spectral densities of velocity fluctuations at polygon 7.7. Depths of measurement: 1, 20 m; 2, 37 m; 3, 55 m; 4 a, b, 77 m; 5, 94 m; 6, 103 m; 7, 121 m; 8 a, b, 138 m; 9, 157 m; 10, 160 m; 11 a, b, 168 m; 12 a, b, 195 m; 13 a, b, 213 m.

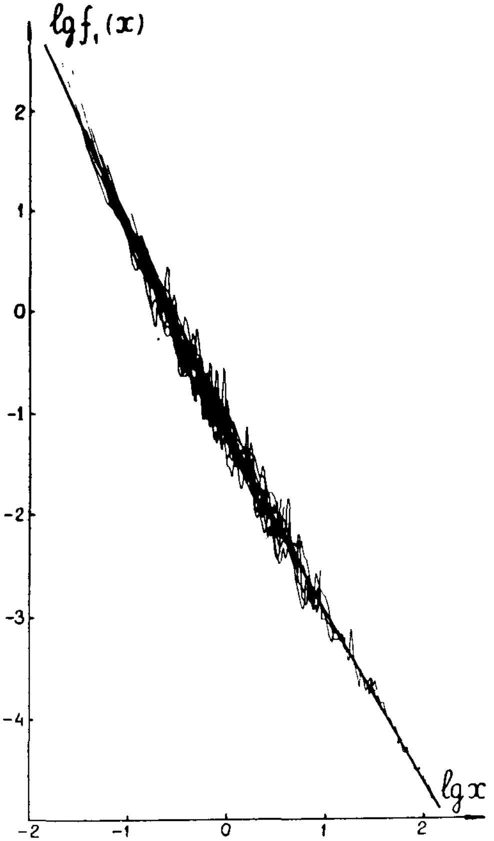

FIG. 11. Comparison of spectra 7.7.u with Monin's model.

It is thus seen that small-scale turbulence in a stratified ocean can be caused by different processes which vary in space and time and lead to a great variety of shapes of spectra for fluctuating fields. The study of the complicated structure of small-scale fluctuations of oceanic fields and its relation to the controlling processes demands further and specially oriented effort.

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