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SEA TURBULENCE SPECTRUM

1. DEFINITIONS AND SCALES

Turbulence is defined as this part of real fluctuations (of hydrodynamical properties) which is not coherent with waves (of any length; nor generally with any „regular" motion). Thus, from a record of a hydrodynamical property one should filter out not only the mechanical and electrical noise, but also the wave-induced fluctuations. The latter can be filtered out if overall real fluctuations ξ (t) are recorded simultaneously with sea level oscillations ξ (t). The filtration procedure was first elaborated by Bowden and White [3] and later Benilov and Filyushkin [1] developed a more general method of linear filtration of stationary random processes. The fluctuations induced by surface waves, ξ (t), can be approximated by the finite sum:

$$\hat{\xi}_n(t) = \sum_{k=1}^{n} \beta_k^{(n)} \zeta(t - t_k^{(n)}) \tag{1}$$

in which the coefficients $\beta_k^{(n)}$ are determined from the system of equations:

$$B_{\xi\zeta}(t_l^{(n)}) = \sum_{k=1}^{n} B_k^{(n)} B_{\xi\zeta}(t_l^{(n)} - t_k^{(n)}) \tag{2}$$

$$l = 1, 2, \dots n$$

where: $B_{\zeta\zeta}(\tau)$ = correlation function for waves $\zeta(t)$,
$B_{\xi\zeta}(\tau)$ = cross-correlation function of real fluctuations and waves.

The mean square error of filtration:

$$\sigma_n^2 = \left| \hat{\xi}^{(t)} - \hat{\xi}_n{}^{(t)} \right|^2 \tag{3}$$

is determined by the formula:

$$\sigma_n^2 = \int_{-\infty}^{+\infty} \left| \frac{f_{\xi\zeta}(\omega)}{f_{\zeta\zeta}(\omega)} - \sum_{k=1}^{n} \beta_k{}^{(n)} e^{-it_k^{(n)}\omega} \right|^2 f_{\zeta\zeta}(\omega)\, d\omega \tag{4}$$

in which $f_{\zeta\zeta}(\omega)$ and (ω) are respective Fourier transformations of the correlation functions $B_{\zeta\xi}(\tau)$ and $B_{\xi\zeta}(\tau)$. The amount of components in the sum of (4), n, can be chosen so as not to surpass a pre-set error level $\varepsilon \geqslant \sigma_n^2$.

Should both processes, $\xi(t)$ and $\zeta(t)$, turn out to be interrelated in the non-linear form:

$$\xi(t) = g[\zeta(s)] \tag{5}$$

there will be a principal possibility of discriminating $\hat{\xi}(t)$ by employing the non-linear filtration model of Benilov [2]. The descrimination is based on known statistical moments:

$$\begin{aligned} B\,\alpha_1 \ldots \alpha_r \xi &= \overline{\xi_1^{\alpha_1} \ldots \zeta_r^{\alpha r} \xi}; \; B\,\beta_1 \ldots \beta_r = \overline{\xi_1^{\beta_1} \ldots \xi_r^{\beta r}} \\ B\,\alpha_1 \ldots \alpha_r \cdot \xi_r &= \overline{\zeta_1^{\alpha_1} \ldots \xi_r^{\alpha r} \xi_T} = 0 \end{aligned} \tag{6}$$

in which α_i, β_i = arbitrary integers, and where, for a known non-linear function $g[\zeta(t)]$, the turbulent part of ξ, i.e. ξ_T can be found from:

$$\xi_T(t) = \xi(t) - \hat{g}[\zeta(s_K)] \tag{7}$$

Fig. 1 shows an example of linear filtration carried out by Benilov [2], who used synchronous recordings of real temperature fluctuations $\xi(t)$ at a depth of 0.5 m and water surface oscillations $\xi(t)$ in the Mediterranean.

An analogous filtration of the fluctuations of hydrodynamical properties due to internal waves is impossible, because the latter are not recorded separately. However, Kolmogorov suggests [4] consideration of the random vectorial field $\vec{u}(x, y, z, t)$ (e.g. velocity field) through the spectral measure $\mathbf{Z}(M)$ (in which M are sets in the plane of horizontal wave vectors $\vec{k}$, the measure $\mathbf{Z}$ depending on the vertical coordinate z and time t). For each fixed k one would discriminate the component:

$$z^o = \frac{1}{k^2} ([\vec{n} \cdot \vec{k}]\, Z)\, [\vec{n} \cdot \vec{k}] \tag{8}$$

in the horizontal plane perpendicular to $\vec{k}$ (where $\vec{n}$ is a unit vector in the vertical direction) and the component:

$$Z^1 = \frac{1}{k^2} (\vec{k} \cdot \mathbf{Z})\, \vec{k} + (\vec{n} \cdot \mathbf{Z})\vec{n} \tag{9}$$

in the vertical plane which contains $\vec{k}$. In this case the field:

$$\vec{u}^{o} = \int \exp [i (k_x \cdot x + k_y \cdot y)] \mathbf{Z}^{o} (\vec{dk}) \quad (10)$$

would describe the horizontal turbulence, while the field:

$$\vec{u}^{1} = \int \exp [i (k_x \cdot x + k_y \cdot y)] \cdot \mathbf{Z}^{1} (\vec{dk}) \quad (11)$$

would contain both turbulence and waves, the latter two being distinguishable from each other only in the spectral bands which do not coincide.

Prospects of the discrimination of turbulence and internal waves can be linked with the application of phase relationships (phase shift spectra) to the fluctuations of various spatial components of velocity and scalar fields, which are fixed for internal waves and arbitrary for turbulence. However, appropriate algorithms for the filtering of internal waves from real fluctuations still remain to be derived.

The problem of the discrimination of turbulence is also crucial in the presence of ther modes of sea motion. Some of these modes are "regular" and well discernible (e.g. lower tidal harmonics), while others are highly random and merge with the turbulent background. From the spectra measured, one is often unable to tell turbulence from the "regular" factors sunken in the overall mixture of different effects, notably if those factors produce relatively weak signals. Therefore it is common to assume that turbulence is somehow the measure of our knowledge of the phenomena observed: all factors describable with mathematical tools, which occur in a fairly narrow band of frequencies and wave numbers (and are mostly concentrated around single frequencies and wave numbers), and are predictable (at least statistically) may be called "regular" or "quasi-deterministic", while all the unknown ones are lumped into turbulence. With the progress in marine sciences, an increasing number of turbulent domains will probably be ascribed to "regular" factors. Nonetheless, the present status of sea dynamics does not allow us to claim as "regular" even some of the largest modes of oceanic motion, because there are certain intractable interaction structures among them. Hence, even though the problem can be approached in numerous ways, it appears to be reasonable to delineate the possible scales of oceanic turbulence.

The smallest fluctuations to be encountered in the ocean are controlled by molecular forces. From the theory of isotropic turbulence their scales (characteristic dimensions) of length and time can be determined as:

$$L_{min} = \eta = \left(\frac{\nu^3}{\varepsilon}\right)^{1/4}; \quad T_{min} = \left(\frac{\nu}{\varepsilon}\right)^{1/2} \quad (12)$$

which correspond to 0.03... 1 cm and 0.1... 100 s for the real range of ν and ε. On the other extreme, the largest length scales are limited by the size of seas and oceans, so that they reach 1000... 10 000 km. However, a single figure must not be given for the maximum time scale, because there are not only diurnal and monthly changes in the structure of sea motions but also seasonal, interannual and even long-wave climatic variations that control the condition of turbulence. All these spatial and temporal changes are coupled with certain "regular motion" factors, between which turbulent noise is present. The energy of those factors (e.g. solar radiation or wind) transferred to sea water, first to the "regular motion" (e.g. to density currents or wind-driven circulation) and next to turbulent eddies of diminishing size (although the generation of the mean motion might also take place through eddies) *. Each mode of mean motion creates its own cascade of turbulent eddies, and other series result from numerous interactions. Even though the number of "regular" motions can be fairly high, the input of energy is significant only at certain wavenumbers and thus, for the sake of practical considerations, it is expedient to choose a few characteristic ranges of turbulence between pronounced bands of energy input, i.e. "regular motion" factors. One of these bands belongs to wind waves and swell, their characteristic scales being 10... 100 m and 1... 10 (... $>$ 10) s. The turbulent eddies between these scales and the smallest ones defined by Eq. (12) form the fine turbulence range. The adjacent mesoturbulence interval stretches up to scales of 1... 10 km and hours... (1) day (s), which correspond to inertial (often tidal) oscillations. The largest eddies are contained in the macroturbulence range, which is fed by the global circulations of the maximum scales mentionad above. It is worth mentioning that microturbulent eddies are sometimes distinguished, up to scales of 1 m and 1 s.

2. SPECTRAL DENSITY FUNCTIONS

The form of oceanic turbulence energy spectrum with three characteristic bands of energy input is depicted in Fig. 2. Ozmidov, who first suggested the existence of such a spectrum, assumed that the turbulence is locally isotropic everywhere between the energy input peaks. Isotropic turbulence is described by the exponent "—5/3" in the power law S = S (k). The existence of this law has been confirmed by the evidence of numerous measurements of water velocities and other physical quantities in the sea. One proof of this kind is also shown in Fig. 1 where the turbulent noise (temperature fluctuations after filtering) displays the

* Energy must not necessarily flow from longwave components to those of higher frequencies, e.g. wind fluctuations of high frequency can induce longer fluctuations of water velocity (by shear stress).

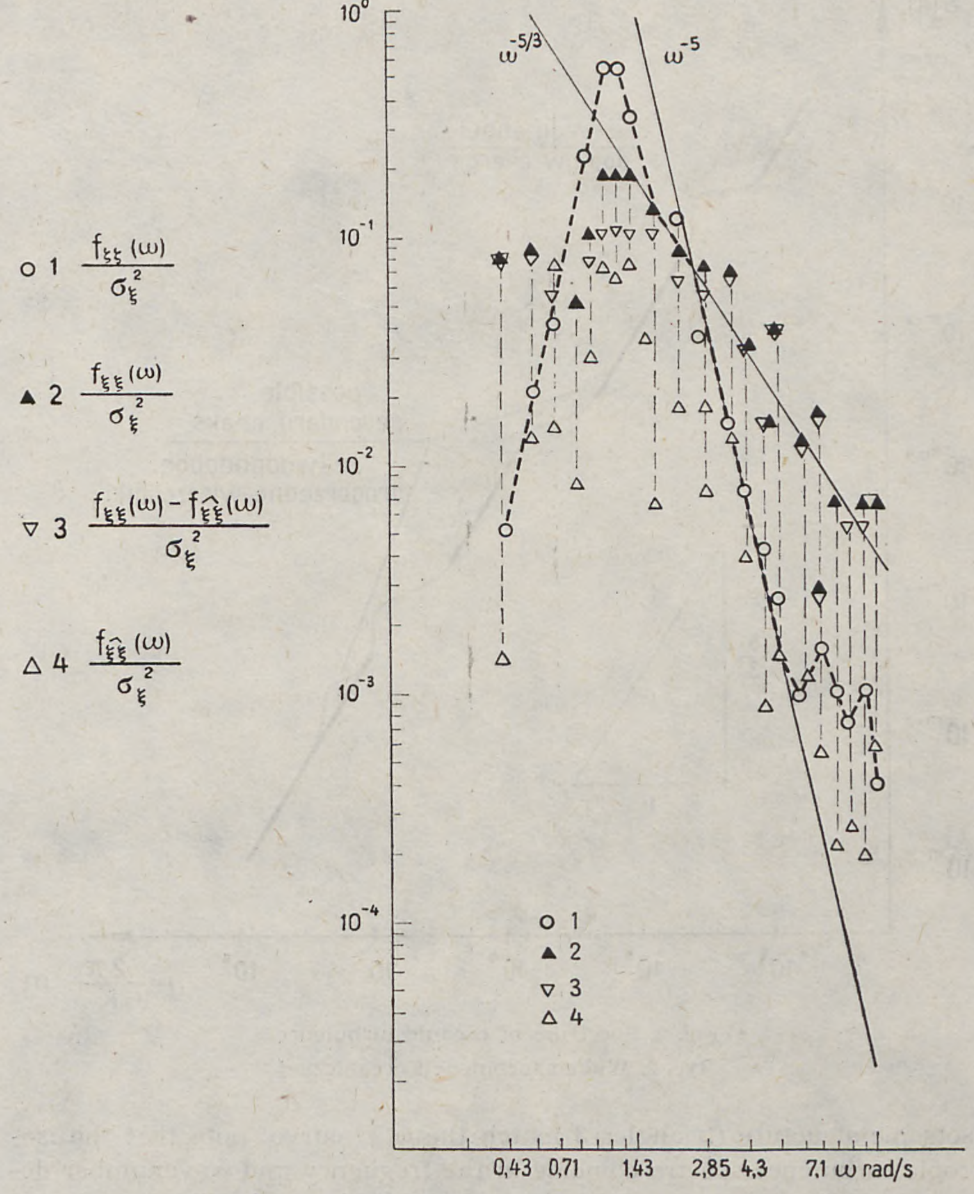

Fig. 1. Examples of spectral densities of wave heights (1), real fluctuations of temperature at depth of 0.5 m (2), filtered fluctuations of temperature (3) and "wave noise" (4) after Benilov (1973)

Ryc. 1. Przykładowe gęstości widmowe wysokości fal (1), rzeczywistych fluktuacji temperatury na głębokości 0,5 m pod powierzchnią morza (2), odfiltrowanych fluktuacji temperatury (3) i „szumu falowego" (4), wg Beniłowa (1973)

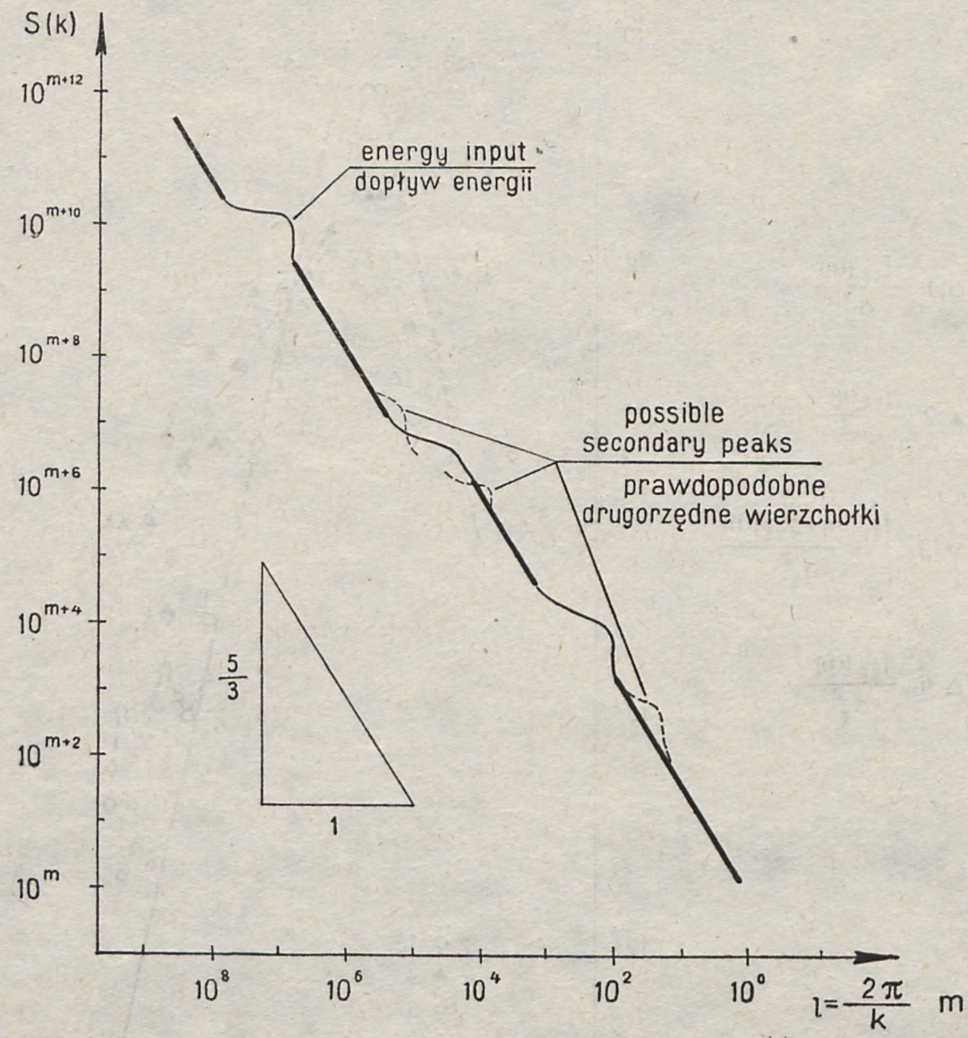

Fig. 2. Spectrum of oceanic turbulence

Ryc. 2. Widmo turbulencji oceanicznej

isotropic structure (triangles 3 match the $\omega^{-5/3}$ curve; note that the isotropic turbulence spectra coincide in the freguency and wavenumber domains), while the wave noise 4 obeys the well-known "—5" law for wind waves.

Although the amount of data supporting the "—5/3" law is extensive, the law itself must not be regarded as universally encountered under any sea conditions, nor is it the only one to be derived analytically. The laws for isotropic turbulence are based on the assumption that, within the equilibrium range of turbulent eddies, in which the energy transferred to an eddy from lower wavenumbers (frequencies) is balanced by the outflow of energy to smaller eddies, it is only the rate of energy dissipation, ε that controls the energy transfer processes and the shape of the turbulence spectrum. From dimensional analysis it follows that

$$S(k) = C \cdot \varepsilon^{2/3} k^{-5/3} \qquad (13)$$

The same rules of dimensional analysis can be employed in the derivation of spectral formulae under different conditions. In the case of two--dimensional turbulence, aside from other quantities it is the mean square of rotation (so-called enstrophy) that must be conserved, its rate of dissipation being $\bar{\varepsilon}_1$ (S^{-3}). Should this dissipation dominate over a certain section of the inertial range of spectrum (in comparison with the dissipation of kinetic energy at a rate of $\bar{\varepsilon}$), the following formula will be obtained from dimensional analysis for the energy spectrum S (k):

$$S(k) = c_1 \cdot \bar{\varepsilon}_1^{-2/3} \cdot k^{-3} \quad \text{for } 2\pi/L \ll k \ll 2\pi/\eta \qquad (14)$$

in which L = external scale of motion,
η = viscous dissipation scale, as in Eq. (12),
c_1 = constant coefficient.

Along the inertial — convective range of spectrum, where the basic processes of spectral transfer are governed by $\bar{\varepsilon}_1$ and the dissipation of inhomogeneities in the structure of concentration (of a certain substance, these inhomogeneities being measured through $\langle \overline{\delta C^2} \rangle$) at a rate of $\bar{\varepsilon}_c$, the spectral density of concentration can depend only on $\bar{\varepsilon}_1$ and $\bar{\varepsilon}_c$, which yield

$$S_c(k) = C_c \cdot \bar{\varepsilon}_c \cdot \bar{\varepsilon}_1^{-1/3} k^{-1} \quad \text{for } 2\pi/L \ll k \ll 2\pi/\eta_o \qquad (15)$$

in which

$$\eta_o = \max [\eta \cdot (\varkappa/\varepsilon_1^{-1/3})^{1/2}]$$

Under other conditions in the upper layer of sea and in the coastal zone the parameter ε is not a controlling factor. It can be substituted by a characteristic velocity, for instance that of energy inflow from the atmosphere v_* [6]. In such cases, e.g. for wind-driven circulation resulting from shear stresses, one obtains:

$$S_c(k) = C_2 \cdot \bar{\varepsilon}_c \cdot v_*^{-1} k^{-2} \qquad (16)$$

In density — inhomogeneous media, the spectra of temperature fluctuations in the inertial — convective range are described by the Obukhov-Corrsin:

$$S_T(k) = B_1 \cdot \bar{\varepsilon}_T \cdot \bar{\varepsilon}^{-1/3} \cdot k^{-5/3} \qquad (17)$$

analogous to the "—5/3" law for velocity fluctuations, in which:

$\bar{\varepsilon}_T$ = rate of the dissipation of temperature inhomogeneous,

B_1 = constant coefficient (close to 1.1).

Other spectra in these media are subject to alterations due to buoyancy. According to the theory of Obukhov-Bolgiano, this effect becomes pronounced in higher scales $1 \geqslant L_* \bar{\varepsilon}^{5/4} \cdot \varepsilon_T^{-3/4} (\alpha_o g)^{-3/2}$ where $\alpha_o \sim 2 \cdot 10^{-4}$ deg $^{-1}$ = coefficient of thermal expansion of water. In the case of stable stratification, on account of high losses of energy to overcome the buoyancy forces, the dissipation ε should be much lower than the rate of energy transfer in low wavenumbers k and therefore it should not control the form of spectra in this range. Hence, one has:

$$S(k) \sim \varepsilon_T^{2/5} (\alpha_o g)^{4/5} k^{-11/5} \tag{18}$$

$$S_T(k) \sim \varepsilon_T^{4/5} (\alpha_o g)^{-2/5} k^{-7/5} \tag{19}$$

If L_* is of the order of magnitude of η, the interval with laws (18) and (19) can wholly replace the inertial subrange.

Panchev [8] has endaevoured to unite all the laws describing the spectra of turbulence in stratified media. He introduced a single common scale:

$$L = \frac{\varepsilon^{1/2}}{(\beta \cdot \gamma)^{3/4}} \cdot \left(\frac{\varepsilon_T \beta}{\bar{\varepsilon} \cdot \gamma}\right)^{x_2} \cdot \left(\frac{b}{\sqrt{\beta \cdot \gamma}}\right)^{x_3} \tag{20}$$

in which $\beta = \alpha_o \cdot g$, $\gamma = \frac{\partial \bar{T}}{\partial z}$, $b = \left|\frac{\partial U}{\partial z}\right|$.

This scale takes various forms (for example L_*) in the regions of validity of respective factors of Eq. 20. It was assumed that, for stratification stable enough, the transfer of energy in the wavenumbers $k L \leqslant 1$ is much higher than the rate of energy dissipation ε, since the basic portion of energy is used up to work against buoyancy, and only a little energy is passed via inertial range to dissipation interval. As ε is eliminated from the set of controlling factors, one obtains:

$$S(k) \sim \varepsilon_T^{*\,3/2} N^{-5/2} (k L_T^*)^{-5/3-\delta} \tag{21}$$

$$S_T(k) \sim \varepsilon_T \varepsilon_T^{*\,1/2} N^{-5/2} (k L_T^*)^{-5/3+\delta/2} \tag{22}$$

$$S_{WT}(k) \sim \varepsilon^{1/2} \varepsilon_T^* N^{-5/2} (k L_T^*)^{-5/3-\delta/4} \tag{23}$$

in which the index "WT" denotes heat flux:

$$\varepsilon_T^* = \frac{\varepsilon_T \beta}{\gamma}$$

$N^2 = \beta \cdot \gamma$ — Brunt-Väisäilä frequency

$$L_T^* = \varepsilon_T^{*\,1/2} \cdot N^{-3/2}$$

$\delta \geqslant 0$ — arbitrary constant.

The Bolgiano formulae correspond to $\delta = 8/15$, and a considerable number of other formulae may be obtained for various δ. It is worth stressing that some of them can be seemingly similar to the formulae of homogeneous media, although their physical meaning (for stratified media) is totally different.

All the spectral formulae derived by dimensional analysis and similarity theory hold true for universal conditions of well-developed turbulence, characterized by high Reynolds numbers. However, the experiments carried out during recent years have indicated that real sea turbulence is seldom coupled with high Reynolds numbers because it is either confined in shallow waters and stratified media or present only in thin layers of deep-water sea. These findings would imply that universal spectra do not exist, at least for microturbulence. This does not necessarily have to be inconsistent with the results of numerous field measurements, in which all those formulae are supported by experimental evidence, compare e.g. Monin et al. [4], Ozmidov [6, 7] and many marine journals. Although we will not dwell on these sources we will try to prove this consistence by presenting new data, notably for the Baltic, restricting ourselves to homogeneous media.

Fig. 3 shows the spectra of concentration fluctuations measured off

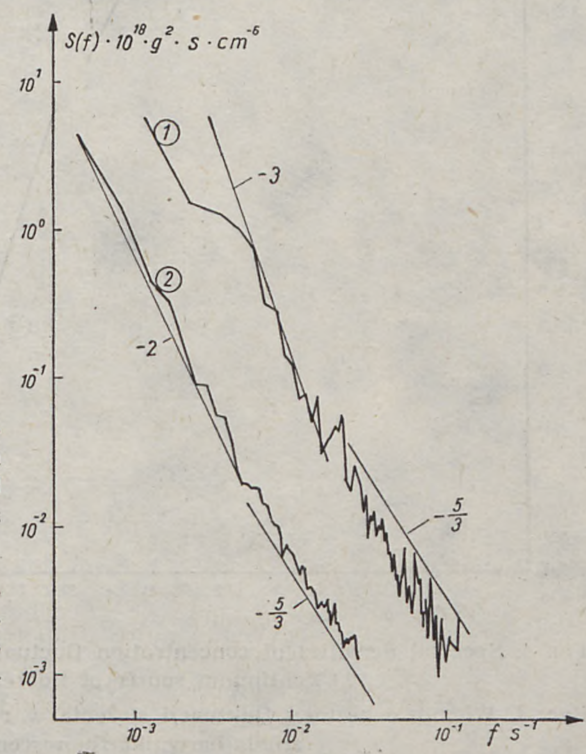

Fig. 3. Spectral densities of concentration fluctuations on 27th September 1974 (curve 1) and 29th September 1974 (curve 2) at Lubiatowo

Ryc. 3. Widmowe gęstości fluktuacji stężenia w dniach 27 września 1974 (krzywa 1) i 29 września 1974 (krzywa 2), pomierzonych w Lubiatowie

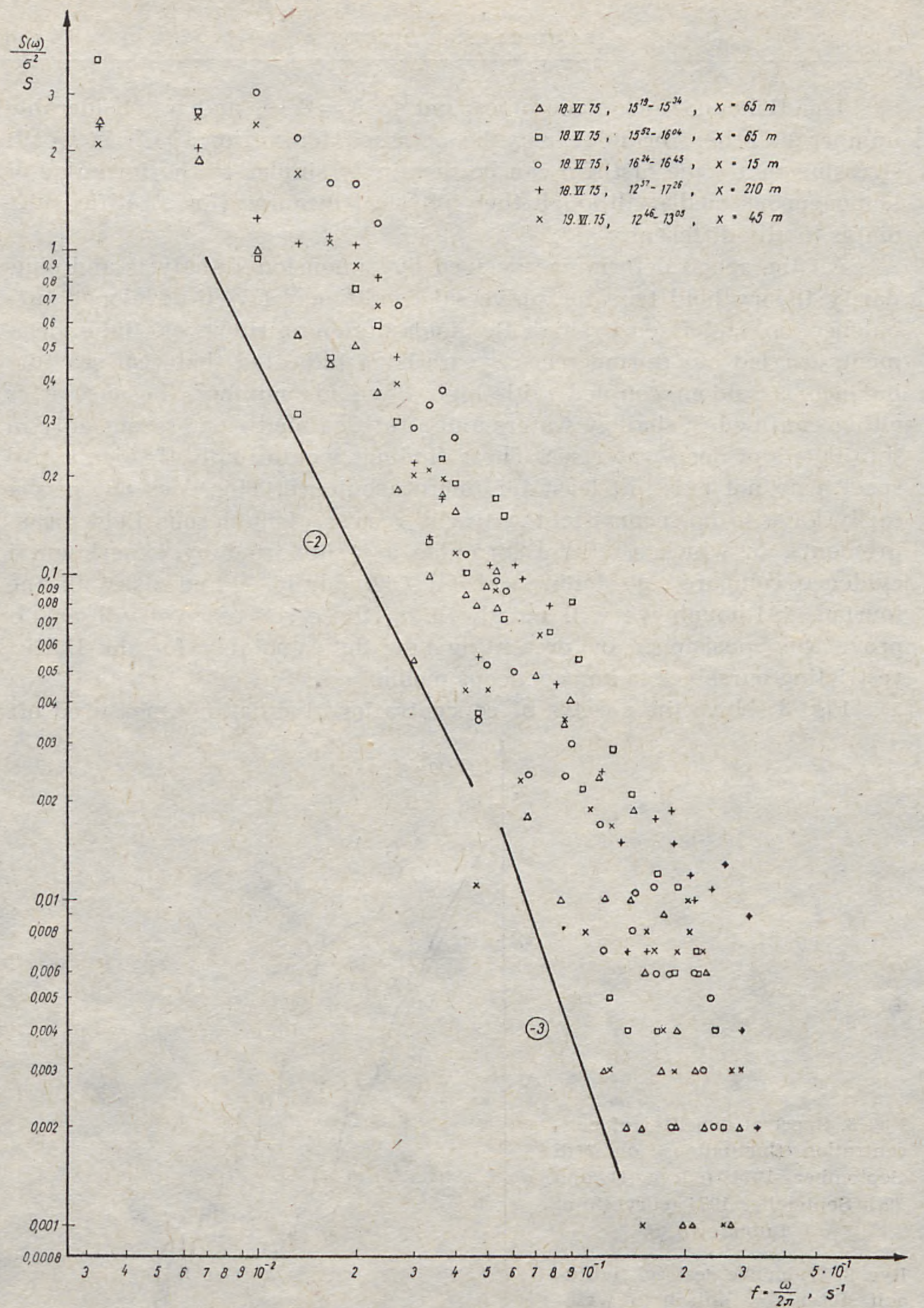

Fig. 4. Spectral densities of concentration fluctuations at different distances from continuous source of fluorescent dye

Ryc. 4. Widmowe gęstości fluktuacji stężenia w różnych odległościach od ciągłego źródła barwnika fluorescencyjnego

Lubiatowo in 5 metres of water at a distance of about 500 m from shore. A stationary fluorimeter, at a depth of about 1 m below the water surface, recorded continuously concentrations of rhodamine being discharged from a source located over 100 m from the fluorimeter. On two days, local isotropy was exposed in higher frequencies while the lower bands displayed the effects of two different factors, viz. sea bed (i.e. two-dimensionality of turbulence) and wind (shear stresses). The same factors were present in another series of measurements, conducted at Darłowo in 1975 (Fig. 4). Here, the fluorimeter was kept fixed at various distances from shore, always about 1 m below the surface and in 6 metres of water, but the duration of measurements was generally shorter than in 1974 (tens of minutes vs 2 hours). Nonetheless, the spectra do not exhibit the "—5/3" law and thus seem to indicate that the ranges of applicability of various spectral laws are mobile and difficult to predict. That this conclusion is virtually true is also shown by the spectra of water velocity in Fig. 5, measured with BPV-type current meters. Because of the discrete mode of readout inherent in these measurements (the quantization periods Δt being shown in parentheses), the presented spectra describe longer eddies with time scales from hours to several days, i.e. correspond to the mesoscale range. Again, the two laws of wind shear and bottom effect, "—2" and "—3", respectively, are present. The two-dimensional character of shallow-water turbulence is more pronounced in the closer proximity of the shore, while the energy transfer from wind to water becomes more distinct further off shore. Energy inflow conditions seem to be delineated at both extremities of the spectra.

Various interaction modes of turbulence are depicted in Fig. 6, in which spectra of water velocities are presented for different depths at various distances from the shore. The velocities were measured with thermistor probes in a Mediterraneon nearshore zone (at Benghazi, Libya). Although the weather was fairly calm, the intensity of turbulence amounted to as much as 30 per cent. The spectra are rather scattered, which might indicate not only a low level of confidence (coupled with the short length of the time series measured — about several minutes), but also presence of various turbulence-generating factors. The wavenumbers of water flow modes induced by these factors lie close to each other, so that the forms of spectral densities depend much on the generation conditions. The basic types of water motion under the conditions illustrated in Fig. 6 are inertial currents, morphological circulation, and swell. They can coincide and merge in certain spectral bands, as shown by dotted lines in Fig. 2. In these cases the inertial subrange (if any) of the lower band spectrum is also occupied by the energy input interval of the high band spectrum. This might elucidate the fact that

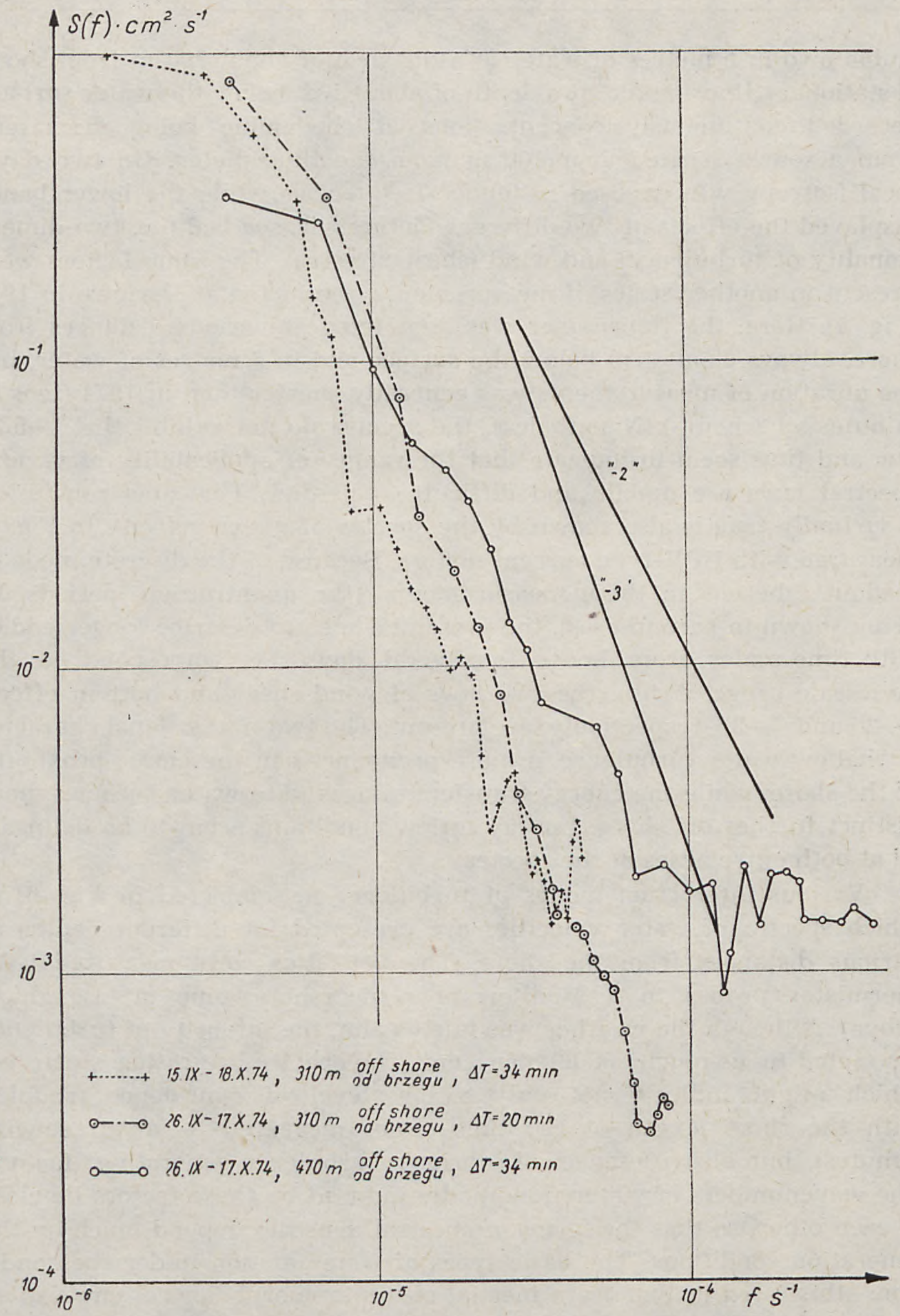

Fig. 5. Spectral densities of water velocities measured under CMEA programme "Lubiatowo 74"

Ryc. 5. Widmowe gęstości fluktuacji prędkości wody mierzonych podczas międzynarodowej ekspedycji RWPG „Lubiatowo 1974"

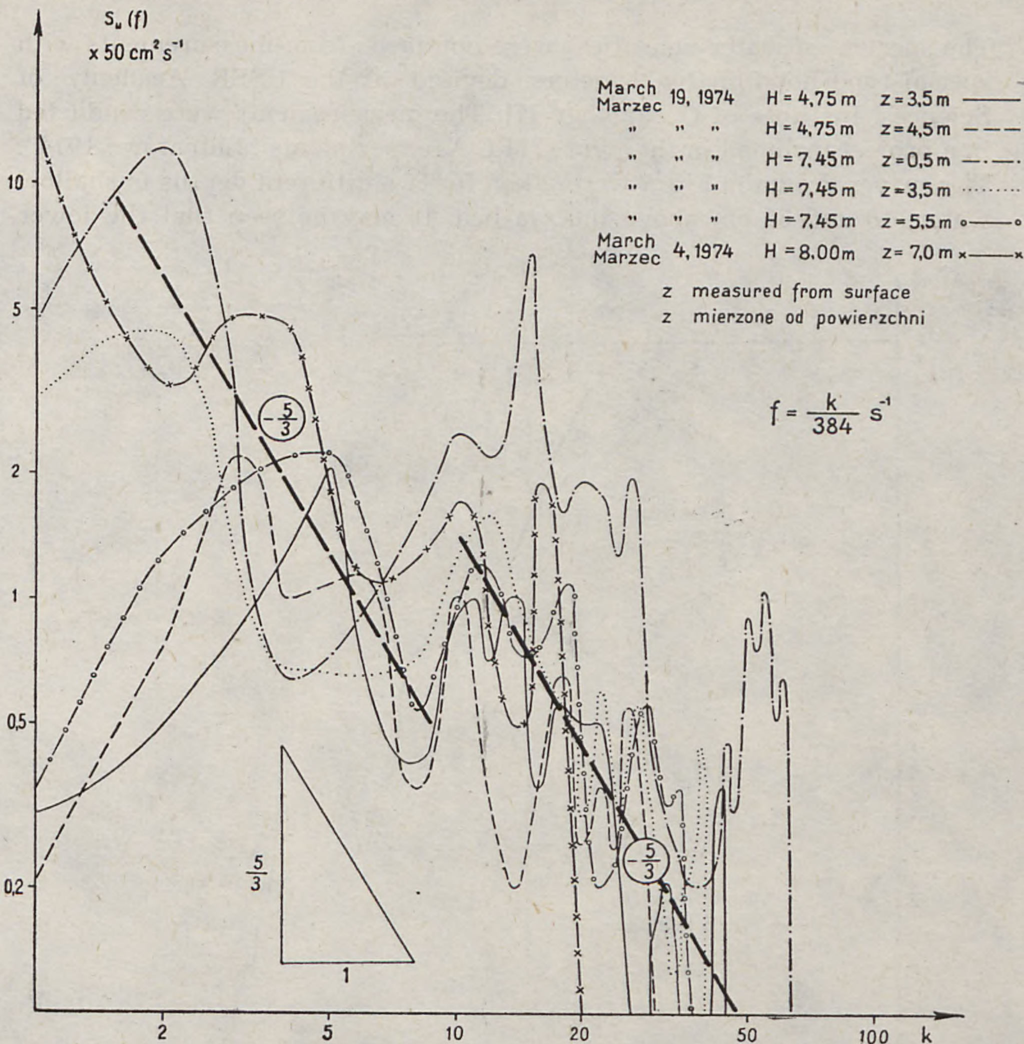

Fig. 6. Water velocity spectra in a Mediterranean coastal zone
Ryc. 6. Widma prędkości wody w brzegowej strefie śródziemnomorskiej

the "—5/3" law has never been found fully acceptable for the coastal zone [9, 10]. It is likely that at least two external energy sources are adjacent in the coastal zone: waves and the morphological interaction between flowing water (driven by external forces) and the sea bed. The morphological Langmuir—type circulation cells might be coupled with local depths. With increasing distance from the shore line, depth increases and the wavenumber of the morphological circulation decreases, thus expanding the interval between both bands of turbulence energy input, sometimes making it wide enough for the "—5/3" law to reappear.

Another example of the water-sea bed interaction is shown in Fig. 7.

The spectra of water velocities were obtained from measurements with special-type hot-film hydrometers devised at the USSR Academy of Sciences' Institute of Oceanology [7]. The measurements were conducted in a project included in the joint C.M.E.A. experiments "Lubiatowo 1974". The curves drawn in Fig. 7 were taken for two different depths in shallow water, 10 and 35 cm above the sea bed. It may be seen that the lower

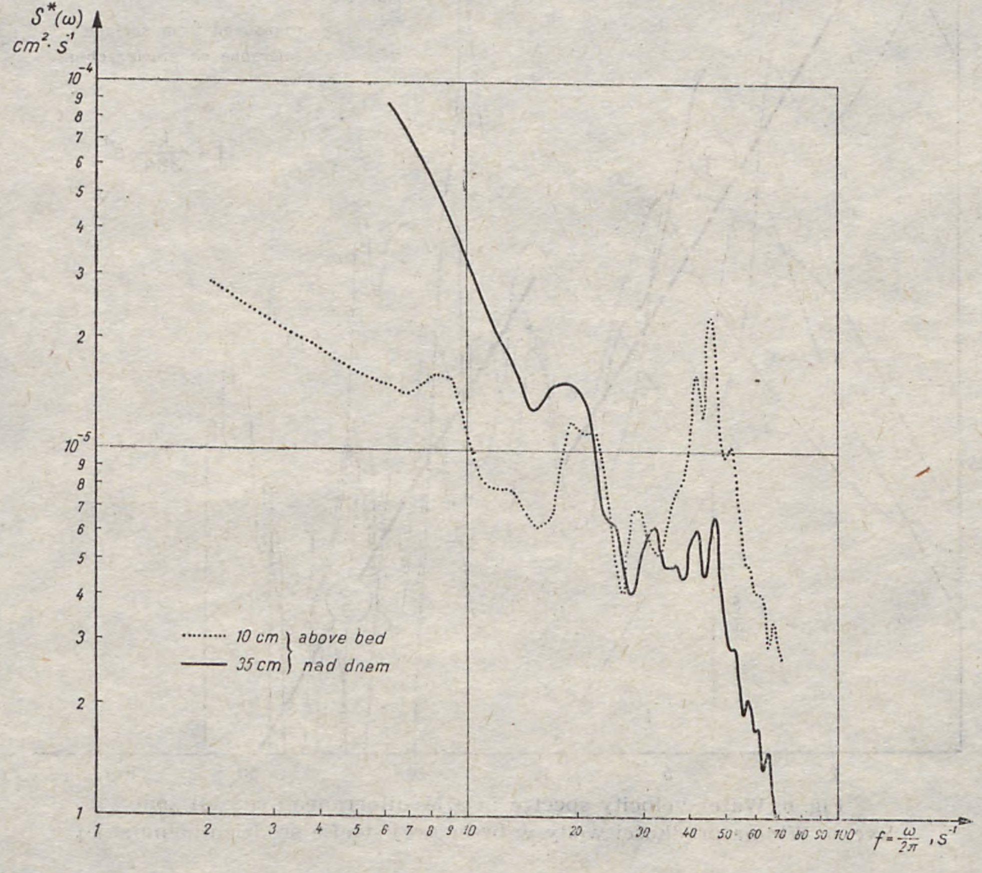

Fig. 7. Microscale turbulence spectra at sea bed

Ryc. 7. Widma turbulencji mikroskalowej przy dnie morza

depth curve (closer to the bed) is much influenced by the energy input, pronounced in the frequencies where the two curves merge. The weak slope of this curve on both sides of the convergence band stems directly from the fact that in the band of energy inflow the spectra are controlled by external factors and are not universal (self-similar). The other curve seems to be disturbed only locally and displays a higher slope of spectrum. It is worth pointing out that both spectra are in high frequen-

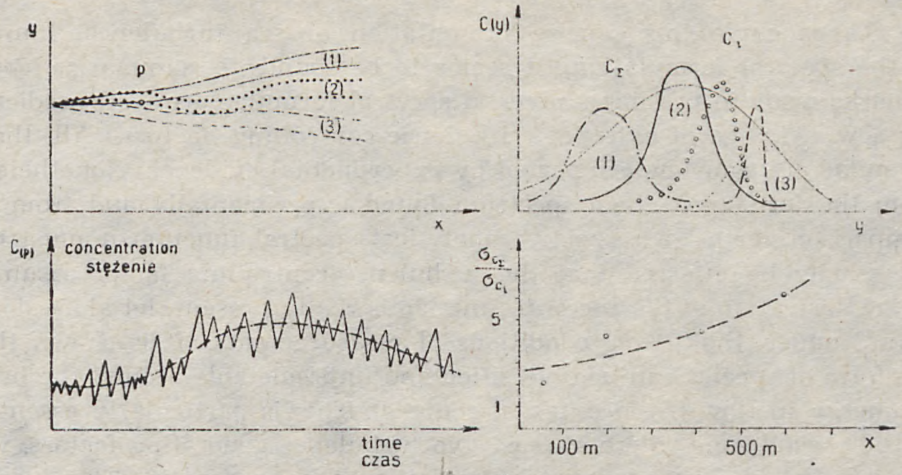

Fig. 8. Multiscale dispersion effects
Ryc. 8. Efekty rozpraszania wieloskalowego

cies, showing the general trend towards local isotropy and other universal conditions also exhibited in microscales.

In has already been shown that diffusion tests, mostly with such tracers as fluorescent dyes and radio isotopes, can aid us to unterstand sea turbulence. Some of the turbulence characteristics of the coastal zone, obtained from statistical analysis of dye concentration fluctuations are discussed elsewhere [5]. They indicate for instance, that the beach acts as a factor of homogenization of microscale eddies: the closer to the shore line a given patch of tracer, the more homogeneous (normal) the statistical distributions of tracer concentrations in the patch. This finding is consistent with the tendencies exposed by the coastal turbulence spectra discussed, herein, primarily with the variety of energy inputs, which enhance mixing processes. Needless to say, the correspondence between the spectral characteristics of turbulence and numerous diffusional quantities is much fuller than it would be implied from the mere analysis of skewness, curtosis, etc. Used as indicators of turbulence conditions may be not only parameters of concentration fluctuations, but also mean concentrations, eddy diffusivities, their derivatives, and many others [9]. Fig. 8 shows how certain diffusion characteristics behave in distinctly different scales of turbulence. The dispersion of a single jet structure is compared with that of a superposition of jets over a longer period of time. Taken at different distances from their source, the ratios of single-jet width to multiple-jet "widt" (more precisely, cross-sectional variances) vary from five to ten, for mesoscale fluctuations with periods as small as a few minutes. For larger turbulent eddies these differences in dispersive effects can be more pronounced.

To conclude this concise presentation of sea turbulence, limited to the spectral formulation, it seems to be sound to summarize some remarks made in passing. Universal spectral formulae are well predicted for a wide range of external turbulence-controlling factors. All these formulae are somehow supported by experimental evidence. Nonetheless, from the form of a given spectrum found experimentally and from its comparison against a respective analytical spectral function it must not necessarily be inferred that the turbulence-controlling factor assumed in the derivation of the spectral function is really present, let alone dominant, under the given conditions of measurements. It is shown that the form of spectra can be diversified and unpredictable around the band of energy in flow (from external sources). This is particularly essential in the coastal zone where at least two turbulence-generating factors, viz. wind waves and morphological circulation, can be present. The energy inflow bands can approach each other and partially merge, thus giving rise to the appearance of a wide variety of spectral functions. Hence, it is highly recommended to provide sufficient "synoptic background" for any measurements of turbulence characteristics. The knowledge of as many hydrophysical fields (wind, wave climate, water densities, etc.) as technologically procurable is crucial to the advancement of sea turbulence. In view of the numerous effects involved, further improvement of sea turbulence forecast models seems to be possible only on the basis of experimental data for the relationships between parameters of turbulence and those of hydrophysical fields.

Since one of the purposes of this short paper was to provoke discussion concentrated around the spectral characteristics, many key problems of turbulence have not even been touched upon. The bibliography of this field becomes more and more ample, so that a mere enumeration of topics would occupy at leasta a few pages. On account of the great scientific as well as technological importance of sea turbulence, it will certainly be devoted more room in this journal.

List of notations

f = frequency
g = acceleration due to gravity
k = wave number
T = temperature
T_{min}, T_{max} = time scales
t = time
S = spectral density function
U, u = velocity
ε = rate of energy dissipation
ν = kinematic coefficient of viscosity

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WIDMO TURBULENCJI MORSKIEJ

Streszczenie

W widmie turbulencji morskiej można wyróżnić twory wirowe drobno-, średnio- i makroskalowe, które zajmują obszar między wielkościami określonymi z jednej strony przez siły molekularne, a z drugiej — przez wymiary mórz. Z każdym „regularnym" średnim ruchem wody morskiej związana jest jego własna kaskada wirowa, a z wzajemnego oddziaływania ruchów średnich i wirów wynikają dalsze kaskady. Dla wielu czynników fizycznych determinujących charakter turbulencji, można wyprowadzić uniwersalne wzory na funkcje gęstości widmowej turbulentnych pulsacji różnych wielkości fizycznych (posługując się przede wszystkim analizą wymiarową i teorią podobieństwa). Wszystkie te wzory dają się potwierdzić doświadczalnie, ale na podstawie zbieżności danych pomiarowych i formuł analitycznych nie można wnioskować o rzeczywistej obecności w naturze tego czynnika, który w formule uznano za dominujący. Wskazano na to, że postać widm turbulencji może być bardzo zróżnicowana i trudna do przewidzenia w sąsiedztwie pasma dopływu energii. Jest to szczególnie istotne w strefie brzegowej, w której mogą występować co najmniej dwa czynniki generacji turbulencji: fale wiatrowe i krążenie morfologiczne. Pasma dopływu energii mogą się tutaj częściowo pokrywać, co pozwala na wystąpienie dużej różnorodności funkcji gęstości widmowych. Z tego względu zalecane jest wykonywanie pomiarów turbulencji przy jednoczesnej rejestracji parametrów szerokiego tła hydrometeorologicznego.

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SPECTRE DE LA TURBULENCE MARINE

Résumé

Dans le spectre de la turbulence marine on peut distinguer des formations tourbillonnaires de micro-, mézo-, et de macro-échelle, qui occupent l'espace situé entre les grandeurs définies par les forces moléculaires d'une part, et par les dimensions des mers d'autre part. A chaque mouvement „régulier" moyen de l'eau de la mer, est liée propre cascade tourbillonnaire, et les autres cascades résultent de l'interaction des mouvements moyens et des tourbillons. Pour de nombreux facteurs physiques dominant les caractères de la turbulence, on peut déduire les formules universelles des fonctions de densité spectrale des pulsations de turbulence de diverses grandeurs physiques (en se servant essentiellement de l'analyse dimensionnelle et de la théorie de similitude). Toutes ces formules peuvent être vérifiées expérimentalement, mais la convergence entre les données des mesures et les formules analytiques ne permet aucunement d'affirmer la prèsence, dans la nature, du facteur qui a été reconnu dominant dans la formule. Ceci résulte du fait que la forme du spectre de turbulence peut être très différenciée et difficilement prévisible au voisinage de la zone d'afflux de l'énergie. Ceci est particulièrement important dans la zone côtière où peuvent se manifester au moins deux facteurs de génération de turbulence: les ondes de vent et la circulation morphologique. A cet endroit, les zones d'afflux de l'énergie peuvent se recouvrir partiellement, ce qui permet l'apparition d'une grande variété de fonctions de densité spectrale. C'est la raison pour laquelle il est recommandé d'effectuer les mesures de la turbulence conjointement à l'enregistrement des paramètres d'un large fond hydrométéorologique.

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