Phys. Oceanogr., Vol. 11, No. 6, pp. 495–508 (2000)

Thermohydrodynamics of the Ocean

Evaluation of the influence of surface films on short wind waves and the characteristics of the boundary layer of the atmosphere*

S. A. GRODSKY, V. N. KUDRYAVTSEV, and V. K. MAKIN

Abstract – With the help of a combined model of wind and waves, we study the influence of films of surfactants on the spectrum of short wind waves and the parameters of the lowest layer of the atmosphere. It is shown that the films of surfactants decrease the roughness of the sea surface as a result of suppression of short wind waves, which decreases the coefficient of resistance of the sea surface and the coefficient of turbulent heat exchange. The maximum influence of films on the exchange coefficients is attained for $U \sim 10\,\text{m/s}$. In this case, the relative decrements of the coefficients of resistance and turbulent heat exchange are equal to 15 and 9%, respectively.

INTRODUCTION

The physical phenomenon of suppression of the short-wave part of the spectrum of wind waves by films of surfactants is well known for a long period of time (see, e g, [1]). The films not only suppress short waves but also decrease the energy of longer waves (although to a lesser extent). This phenomenon is frequently used by sailors under stormy conditions. The smoothed parts of the sea surface are called slicks and have various shapes and sizes. Their length varies within the range from tens of meters to several kilometers. Most often, slicks are formed in the zones of elevated biological productivity and in the regions of artificial pollution. Natural biological (soluble) films are formed as a result of the adsorption of biological impurities from the thickness of water and the artificial (insoluble) films are formed, as a rule, as a result of spread of pollutions, such as petroleum or various kinds of oil, over the surface.

The theory of damping of short wind waves by surfactants is developed in [2, 3] on the basis of fundamental results that can be found in [4]. An additional dissipation of surface waves is formed by the work of tangential forces appearing as a result of spatial nonuniformity of the concentration of the film (surface tension) in the field of the orbital velocity of waves. In this case, the damping decrement is determined by the sole parameter of the film, namely, by its modulus of elasticity.

Surface films play an important role in applications connected with the remote sounding of the ocean because they strongly affect short wind waves determining the interaction of the electromagnetic fields with the sea surface within the band of SHF

---

* Translated by Peter V. Malyshev and Dmitry V. Malyshev

UDC 551.46

radio waves [5] and take part in the formation of signals in the optical and infrared parts of the spectrum.

Surface waves significantly affect the processes of momenta, heat, and moisture exchange between the ocean and the atmosphere. Integral parametrizations relate these flows to the data of measurements of winds, temperature, and humidity at a standard level via the coefficient of resistance of the sea surface and the coefficients of heat and moisture transfer. As one of the results obtained with the help of the combined model of wind and waves developed in [6–8], one can mention the fact that the contribution of short wind waves to the formation of the coefficient of resistance of the sea surface is determining. Thus, surface films may potentially affect the large-scale interaction between the ocean and the atmosphere modifying the short-wave part of the spectrum of waves. The intensity of this influence depends, parallel with other factors, on the fraction of the sea surface covered with surfactants. According to the data presented in [9], the relative surface occupied by slicks can be significant. It is determined by the wind velocity U and decreases from 50–60% for $U = 2\,\mathrm{m/s}$ to 20–30% for $U = 4$–$6\,\mathrm{m/s}$.

The aim of the present work is to evaluate the influence of the films of surfactants on the spectrum of waves and some parameters of the interaction of the ocean with the atmosphere. Our research is based on the use of the combined model of wind and waves [7, 8].

PRINCIPAL RELATIONS OF THE COMBINED MODEL OF WIND AND WAVES

A model of the spectrum of short wind waves developed in [8, 10] follows from the following stationary and horizontally uniform energy balance equation:

$$\beta_v B + \tilde{D}(K, \varphi)F - \tilde{D}(k, \varphi) = 0 \qquad (1)$$

presented in the dimensionless form for the spectrum of saturation $B(k, \varphi) = k^4 S(k, \varphi)$, where S is the spectrum of elevations, k is the wave number, and φ is a direction of propagation of the wave component. The parameter $\beta_v = \rho_a \beta / \rho_w - \gamma$ describes the inflow of energy from the wind minus viscous dissipation; here, ρ_a and ρ_w are the densities of air and water, respectively, and β is the coefficient of wind–wave interaction. The remaining terms in (1) have the following physical meaning:

The dimensionless dissipation $\tilde{D}(k)$ is introduced in [8], where the following functional relationship proposed in [11] is substantiated:

$$\tilde{D}(k, \varphi) = \left(\frac{B(k, \varphi)}{\alpha}\right)^n B(k, \varphi). \qquad (2)$$

The second term in (1) describes the nonlinear generation of a capillary wave

$$k > k_c = \sqrt{\frac{\sigma}{g\rho_w}}$$

on the crest of a gravitational wave (with wave number K) with the same phase velocity $c(K) = c(k)$, where $K = k_c^2/k$ and σ is surface tension. The range of action of this mechanism is restricted by the range of capillary waves and is formally given by a function

$$F = \exp\left[-4\left(\frac{k_c}{k}\right)^4\right].$$

The results of laboratory experiments presented in [12] demonstrate that the growth of the energy of a gravitational wave leads either to its breaking for $\lambda >$ 10 cm or to the generation of a packet of "parasitic" capillaries on its front slope ($\lambda <$ 10 cm). Therefore, the function F differs from zero only for $k < 2100$ rad/m and bounds the zone of gravitational waves ($K > 62.8$ rad/m) whose dissipation is caused not by breaking but by the generation of "parasitic" capillaries.

The spectrum of short wind waves is constructed by conjugating the solutions of equation (1) for the gravitational and capillary intervals at $k = k_c$:

$$B(k, \varphi) = \alpha\left[\frac{\beta_\nu(k, \varphi) + (\beta_\nu^2(k, \varphi) + \tilde{D}(K, \varphi)F)^{1/2}}{2}\right]^{1/n}. \tag{3}$$

The fitting functions of the model have the form

$$\ln\alpha = \ln\frac{\alpha_{cg}}{\alpha_g}\Phi\left(\frac{k}{k_c}\right) + \ln\alpha_g, \quad \frac{1}{n} = \left(1 - \frac{1}{n_g}\right)\Phi\left(\frac{k}{k_c}\right) + \frac{1}{n_g},$$

$$\Phi\left(\frac{k}{k_c}\right) = \min\left[\left(\frac{k}{k_c}\right)^m, 1\right]. \tag{4}$$

The parameters $n_g = 2$, $\alpha_g = 0.0388$, $\alpha_{cg} = 0.174$, and $m = 1$, are chosen from the condition of the best possible agreement with the data of the measurements. The spectrum of short wind waves (3) is true for $k > 10k_p$ (k_p is the wave number of the peak) and conjugates with the spectrum of energy-carrying waves [13].

The coefficient of wind-wave interaction β and the laws of resistance were obtained in [7] on the basis of the analysis of the structure of the wave boundary layer (WBL). Within the WBL ($z_0^\nu < z < h$), the vertical flows of angular momentum τ and heat τ^θ are constant:

$$\tau(z) = \tau^t(z) + \tau^w(z) = u_*^2, \quad \tau^\theta(z) = u_*\theta_*, \tag{5}$$

where u_* and θ_* are, respectively, the dynamic velocity and temperature at $z = h$. The total Reynolds stress $\tau(z)$ is formed by turbulent $\tau^t(z)$ and wave-induced $\tau^w(z)$ stresses. The ratio of the wave flow of momenta on the surface to the total flow is used as a parameter of wind-wave coupling α_c:

$$\alpha_c = \frac{\tau^w(0)}{u_*^2}. \tag{6}$$

The wave stresses on the surface can be expressed via the spectrum of the flow of momenta to the waves

$$\tau^w(0) = \int T(k)\, d(\ln k)$$

determined by the parameter of wind-wave interaction $\beta(k, \varphi)$ and the spectrum $B(k, \varphi)$ as

$$T(k) = \int_{-\pi}^{\pi} c^2 B(k, \varphi)\beta(k, \varphi)\cos\varphi\, d\varphi. \tag{7}$$

The wave stresses depend on the height and are close to zero on the upper boundary of the WBL. Its vertical profile is described by a function

$$\tau^w(z) = \tau^w(0) f(z), \tag{8}$$

satisfying the conditions $f(0) = 1$ and $f(h) \to 0$. The function $f(z)$ is determined in [7] on the basis of parametrization of numerical calculations.

The coefficient of wind-wave interaction is taken in the form $\beta \sim u_*^2/c^2$ proposed in [14]. In this case, the global dynamical velocity u_* is replaced with the local velocity $u_*^2(z) = \tau^t(z) = u_*^2(1 - \alpha_c f(z))$ averaged over the layer $\delta(k)$ determining the generation of the wave component k:

$$\beta = 32(1 - \alpha_c f(k))\, \frac{u_*^2}{c^2} \cos\varphi\, |\cos\varphi|, \tag{9}$$

where

$$f(k) = \frac{1}{\delta}\int f(z) \exp\left(-\frac{z}{\delta}\right) dz$$

is the averaging function determined by the profile of wave stresses.

The laws of resistance for momenta and turbulent heat exchange have the form [7, 15]

$$C_D^{1/2} = \frac{\kappa}{\int_{z_0}^{z} \Phi(z/L)[1-\alpha_c f(z)]^{3/4}\, d(\ln z)}, \quad C_H = \frac{\kappa C_D^{1/2}}{\int_{z_0}^{z} \frac{\Phi^{\theta}(z/L)\Pr d(\ln z)}{[1-\alpha_c f(z)]^{1/4}}}, \tag{10}$$

where $z_0^{\nu} = 0.1\nu(1-\alpha_c u_*)^{-1/2}$ is the viscous scale of roughness. The heat Prandtl number in air Pr is equal to 0.9 for unstable stratification and, for stable stratification, Pr = 1.25. In (10), the effects of stratification are taken into account phenomenologically via the dimensionless flow functions Φ specified by the Monin–Obukhov length scale L proposed in [16].

INFLUENCE OF THE FILMS OF SURFACTANTS ON THE SPECTRUM OF WIND WAVES

An additional source of dissipation of wind waves caused by surface films is easily taken into account by replacing viscous dissipation on the clean surface $\gamma = 4\nu_w k^2/\overline{\omega}$ with the corresponding dissipation for the sea surface covered with a film of surfactant. For this purpose, we use a very simple model based on the assumption that surfactants affect the linear dissipation of waves only due to the visco-elastic properties of the films. According to [4], the elastic modulus of the film E is, in the general case, a complex variable and can be expressed via the surface concentration of the film Γ by the formula

$$E = \frac{\dfrac{d\sigma(\Gamma)}{d(\ln \Gamma)}}{1-(i-1)\dfrac{\sqrt{D_\nu}\,\partial C}{2\overline{\omega}\,\partial\Gamma}}, \tag{11}$$

where $D_\nu = \nu_w/\Pr_D$ is the coefficient of molecular diffusion ($\Pr_D \sim 1000$ is the diffusion Prandtl number in water), C is the bulk concentration of the substance which is adsorbed on the surface to form the film. For insoluble films, $C = 0$ and the imaginary part of the elastic modulus $\operatorname{Im} E = 0$. In the general case, $E = E_d + iF_i$ and γ has the form [17]

$$\gamma = \frac{4\nu k^2}{\overline{\omega}} \frac{1 - \dfrac{(E_d - E_i)k^2}{\rho_w \overline{\omega}^{3/2}\sqrt{2\nu}} + \dfrac{|E|^2 k^3}{4\sqrt{2}\rho_w^2 \nu^{3/2}\overline{\omega}^{5/2}} + \dfrac{E_i k}{4\rho_w \nu\overline{\omega}}}{1 - \dfrac{\sqrt{2}(E_d - E_i)k^2}{\rho_w \overline{\omega}^{3/2}\sqrt{\nu}} + \dfrac{|E|^2 k^4}{\rho_w^2 \nu \overline{\omega}^3}} \tag{12}$$

Films increase the decrement of damping of waves both due to the fact that the elasticity modulus is nonzero and as a result of changes in the dispersion relation $\overline{\omega}(k)$, which depends on the coefficient of surface tension. To describe the elastic properties of the film, we use the virial equation of state proposed in [18]

$$\pi A = C_0 + C_1 \pi + C_2 \pi^2, \tag{13}$$

where $\pi = \sigma_0 - \sigma(\Gamma)$ and $\sigma_0 = \sigma(\Gamma = 0) = 74\,\mathrm{dyn/cm}$ is the coefficient of surface tension of clean water. We assume that parameters $C_0 = 85.16\,\mathrm{erg}$, $C_1 = 227.5\,\mathrm{cm}^2$, and $C_2 = 5\,\mathrm{cm}^3/\mathrm{dyn}$ are equal to their mean values observed in the experiments [19]. The variable A (measured in cm^2) is the area occupied by the film in measuring σ with a Langmuir balance. The variable A is regarded as a parameter and, in view of the fact that $\Gamma \sim 1/A$, for the static elasticity of the film, we can write

$$E_0 = \frac{\partial \pi}{\partial \ln \Gamma} = -\frac{\partial \pi}{\partial \ln A}.$$

The results of calculations are presented as a function of E_0.

NUMERICAL RESULTS

We study the influence of surfactant films on the parameters of wind flow over the waves. As follows from the laws of resistance (10), the value of the parameter of wind-wave coupling α_c determines the difference between the structure of WBL and the vertical characteristics of flow over a smooth wall. Indeed, for a nonstratified flow with $\alpha_c = 0$, relations (10) imply the well-known laws of resistance for a flow whose profile is logarithmic and the roughness parameter is equal to the viscous parameter: $z_0 = z_0^{\nu}$. In Fig. 1.1, we present model values of α_c for the clean sea surface and slicks formed by an insoluble film whose elasticity modulus E is equal to 30 dyn/cm (typical of olein). The numerical calculations were performed for various winds and types of stratification of the air–water boundary layer. The influence of stratification on the parameter of the wind–wave coupling is weak. The quantity α_c increases with the wind velocity and, for light winds ($U < 5\,\mathrm{m/s}$), when the effect of damping of waves by the films is maximum, the typical values of α_c are equal to 0.3–0.4.

The influence of the films on the parameters of the WBL is determined both by the quantity α_c and the fraction of α_c formed by sufficiently short wave components efficiently suppressed by the surfactants. According to [20], the range of wave numbers can be estimated as follows: $k < k_s = 20\pi/3\,\mathrm{rad/m}$. The normalized spectra of the wave flow of momenta $T(k)/\tau^w(0)$ presented in Fig. 1.2 show that the contribution of the "slick-forming" wave range to the quantity α_c described by the formula

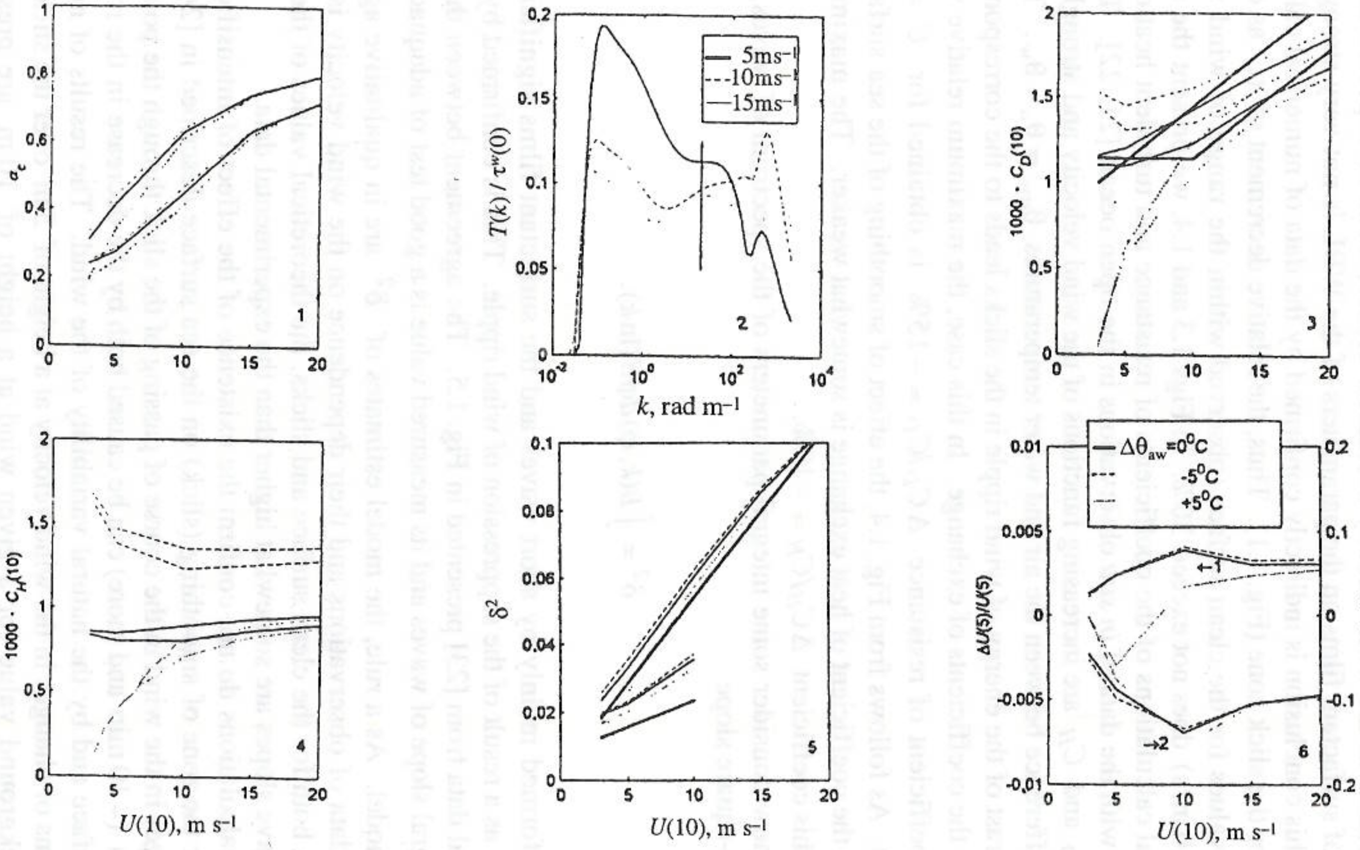

Figure 1. Parameters of the wave boundary layer over the clean surface and over the slick as a function of the wind velocity $U(10)$ for various values of the difference between the air and water temperatures $\Delta\theta_{aw}$: (1) parameter of the wind-wave coupling a_c; (3) coefficient of resistance $C_D(10)$ (solid lines represent the data of [21, 22]); (4) coefficient of turbulent heat exchange $C_H(10)$; (5) dispersion of wave slopes δ^2 (solid lines represent the data of [23]); (6) relative difference of the following values over the slick relative to the background values: (←1) wind velocities at a height of 5 m, $\Delta U(5) / U(5)$; (→2) the coefficient of resistance, $\Delta C_D / C_D$. (2) Normalized spectrum of the vertical flow of momenta to waves $T(k) / \tau^w(0)$ for various wind velocities at a height of 10 m. Vertical line corresponds to $k = 2\pi / 0.3$ rad m-1.

$$\rho = \frac{1}{\tau^w(0)} \int_{k>k_s} T(k)\, d(\ln k)$$

also decreases as the wind velocity decreases. Hence, it can be expected that the influence of surfactant films on the parameters of the WBL is not very strong for any wind. This conclusion is indirectly confirmed by the data of numerical calculations of α_c for the slick zone (Fig. 1.1). Thus, the relative decrement of α_c as compared with its values for the clean surface (observed within the range of wind velocities U = 5–10 m/s) does not exceed 30%. In Figs 1.3 and 1.4, we present the results of numerical calculations of the coefficients of resistance and turbulent heat exchange together with the data of *in situ* observations in the open ocean [21, 22]. The quantities C_D and C_H are increasing functions of the wind velocity and strongly depend on the difference between the air and water temperatures $\theta_{aw} = \theta_a - \theta_w$. The negative contrast of the energy of wind ripple in the slicks leads to the corresponding decrease in the coefficients of exchange. In this case, the maximum relative variation of the coefficient of resistance $\Delta C_D / C_D \approx -15\%$ is obtained for U = 10 m/s (Fig. 1.6). As follows from Fig. 1.4, the effect of smoothing of the sea surface in the slicks on the coefficient of heat exchange is somewhat weaker. The maximum variation of this coefficient $\Delta C_H / C_H \approx -10\%$.

We now consider some integral parameters of the spectrum of waves, namely, the mean-square slope

$$\delta^2 = \int B(k, \varphi)\, d\varphi\, d(\ln k).$$

It is formed mainly by short waves and the surfactant films significantly decrease δ as a result of the suppression of wind ripple. This is confirmed by the experimental data from [23] presented in Fig. 1.5. The agreement between the calculated integral slope of waves and its measured value is a good test of adequacy of the applied model. As a rule, the model estimates of δ^2 are in qualitative agreement with the data of observations and their dependence on the wind velocity is correct. However, both for the clean surface and slicks, the theoretical values of the dispersion of wave slopes are somewhat higher than the experimental data.

Our calculations do not confirm the existence of the effect of intensification of wind over the zone of smoothing (slick) on the sea surface described in [24]. Note that changes in the wind in the course of passing of the slick through the point of observations (~ 10 min and more) can be caused both by the decrease in the roughness of the surface and by the natural variability of the wind. The results of numerical calculations of changes in the wind velocity at a height of 5 m over the slick relative to its background value for a given wind at a height of 10 m are presented in Fig. 1.6. Indeed, the wind velocity becomes somewhat higher over the slick in agreement with the data of observations from [24] but the quantity $\Delta U(5)/U(5)$ does not exceed 0.5% and can be neglected.

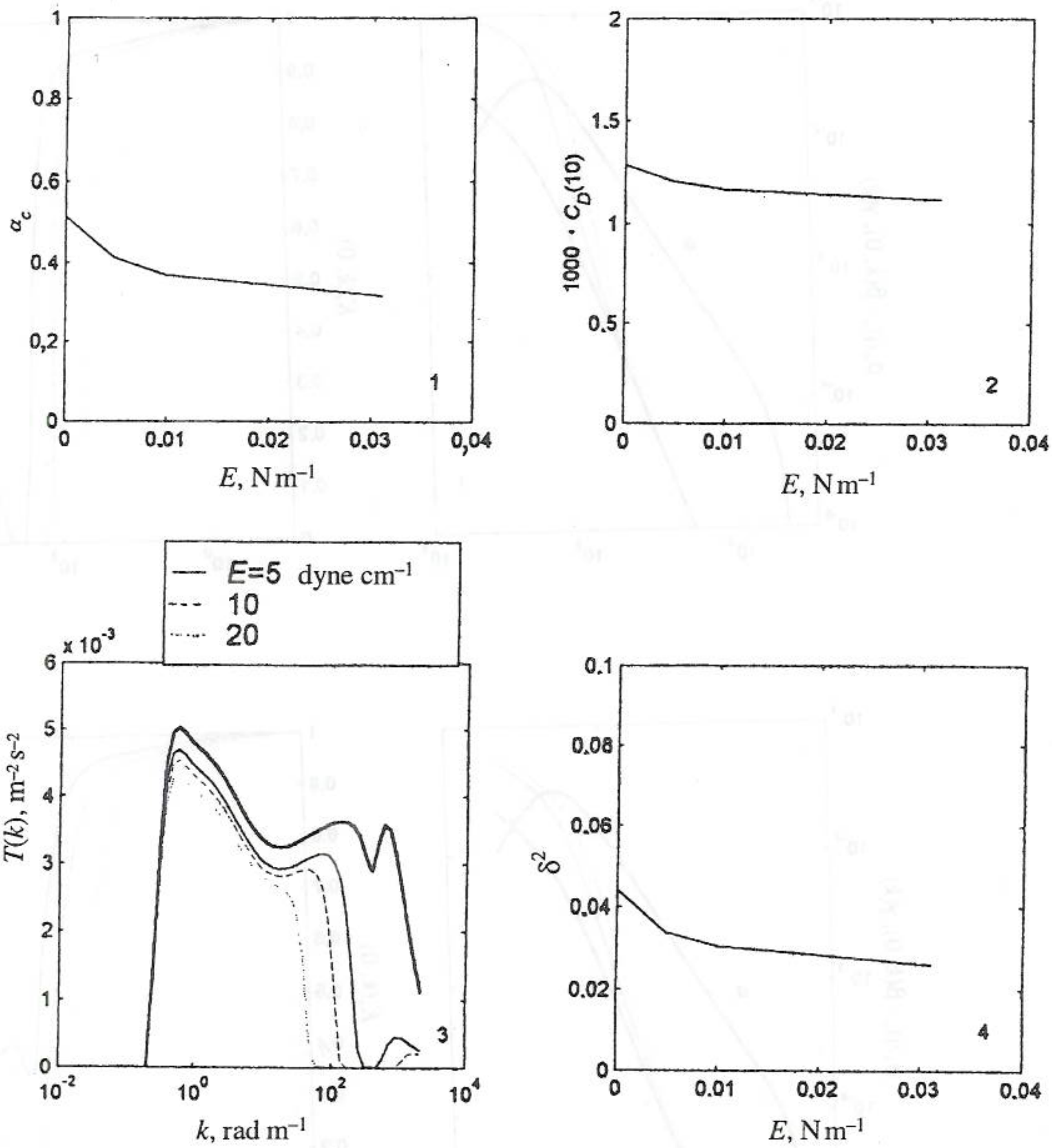

Figure 2. Parameters of the wave boundary layer as a function of the elasticity modulus of an insoluble film E for $U(10) = 7\,\mathrm{m/s}$: (1) parameter of the wind–wave coupling α_c, (2) coefficient of resistance $C_D(10)$, (4) dispersion of wave slopes δ^2, (3) spectrum of the vertical flow of momenta to waves $T(k)$ for various E. The bold solid line corresponds to the data obtained for the clean surface $E = 0$.

Let us now analyze the dependence of characteristics of the WBL on the elasticity of the film. The results of calculations performed for an insoluble film and $U(10) = 7\,\mathrm{m/s}$ are presented in Fig. 2. The case of elasticity equal to zero $E = 0$ corresponds to the clean sea surface. As the quantity E increases, the dissipation of short waves becomes more intense. This results in their suppression and, according to (7), affects the form of the spectrum of the wave flow of momenta $T(k)$ (Fig. 2.3).

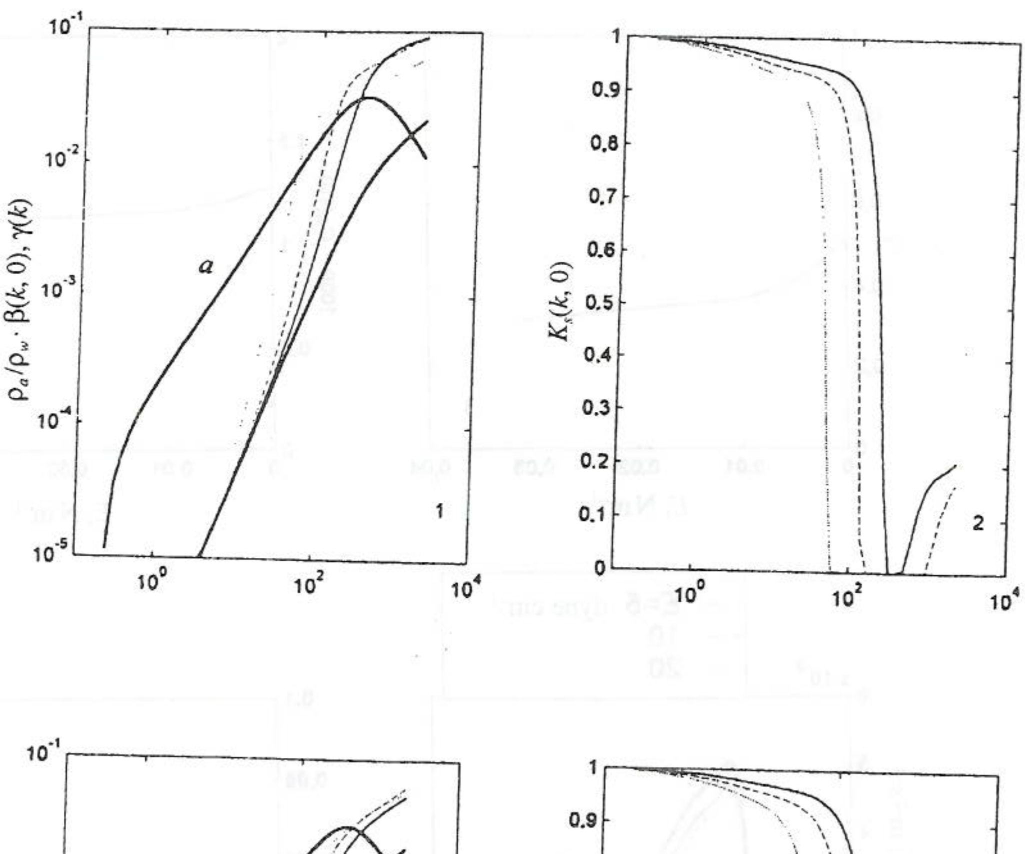

Figure 3. Dependences of the parameter of wind–wave interaction $\beta(k, 0)\rho_a/\rho_w$ and the viscous damping decrement (1, 3) and of the contrast $K_s(k, 0) = S_s(k, 0)/S(k, 0)$ of the level of spectrum in the slick as compared with the clean sea surface for waves propagating parallel to the wind (2, 4) on the wave number k. The upper and the lower rows correspond to insoluble and soluble films, respectively. The calculations were performed for $U(10) = 7\,\mathrm{m/s}$ and different values of the static elasticity of the film E (see Fig.2.3). The bold solid line corresponds to the data obtained for the clean surface.

As a result, the parameter of wind–wave coupling represented as the integral of $T(k)$ decreases (Fig. 2.1). As the elasticity of the film increases, the sea surface undergoes gradual smoothing. This, in turn, decreases the coefficient of resistance of the sea surface (Fig. 2.2) and the mean-square slope of waves (Fig. 2.4).

Spectral contrast is introduced as the ratio of the level of the spectrum in the slick to its level for the clean sea surface for waves propagating along the wind

$$K_s(k, 0) = \frac{S_s(k, 0)}{S(k, 0)}.$$

In Fig. 3, we present the results of calculations carried out for $U(10) = 7$ m/s. Thus, Figs 3.1 and 3.2 contain the results obtained for insoluble films. It follows from (1) that the level of spectrum and contrast of gravitational waves $(k < k_c,\ F \approx 0)$ are determined by the difference between the inflow of energy from the wind and the level of viscous dissipation $\beta_v = \rho_a \beta / \rho_w - \gamma$. In Fig. 3.1, we present the background coefficient of wind–wave interaction $\rho_a \beta(k, 0)/\rho_w$ in the direction of the wind and the viscous damping decrement for the clean surface and in the presence of surfactant films with various values of the static modulus of elasticity. Note that the film with relatively small E equal to 5 dyne/cm significantly increases the value of γ as compared with the case $E = 0$. For $U(10) = 7$ m/s, the wave number k_β satisfying the condition $\beta_v(k_\beta, 0) = 0$ belongs to the zone of gravitational waves. For $k > k_\beta$, the level of spectrum turns into zero because the level of dissipation is higher than the inflow of energy from the wind (Fig. 3.2). The calculations were performed for the cases $E = 5$, 10, and 30 dyne/cm typical of the spread of fuel, vegetable oil, and olein, respectively (see Fig. 3). In these cases, the wavelength $\lambda_\beta = 2\pi / k_\beta$ was equal to 2.5, 4.6, and 13 cm, respectively. Capillary waves $(k < k_s)$ are generated not only by the wind but also, as in the case of "parasitic" waves, on the crests of gravitational waves with wave numbers $62.8 \text{ rad/m} < k < k_\beta$. This results in a saddle-type form of the contrast and the spectral level differs from zero for $k > k_c^2 / k_\beta$. Note that, for a film with the elasticity modulus $E = 30$ dyne/cm, we have $k_\beta <$ 62.8 dyne/cm $(\lambda_\beta > 10 \text{ cm})$ and the contrast $K_s = 0$ for all $k < k_\beta$.

In Figs. 3.3 and 3.4, we present the results of numerical calculations performed for the same wind $U(10) = 7$ m/s for soluble films. In these calculations, the derivative $\partial\Gamma/\partial C$ in (11) (measured in [m]) is estimated according to the diffusion scale of length as $10 D_v \nu_*^{-1}$, where

$$\nu_* = \sqrt{\frac{\rho_a}{\rho_w}}(1 - \alpha_c) u_*$$

is the dynamic velocity of waves in water. It follows from the comparison of Figs 3.1 and 3.3 that, for the same modulus of static elasticity, viscous dissipation is much lower for soluble films than for insoluble. Thus, the wave number $k_\beta > k_c$

belongs to the zone of capillary waves and the spectral level differs from zero in the entire range of k.

CONCLUSIONS

The influence of the films of surfactants on the spectrum of short wind waves and the parameters of the lowest layer of the atmosphere is evaluated on the basis of the combined model of wind and waves proposed in [6, 8]. The parameters of these films were specified on the basis of the coefficient of viscous dissipation obtained in [4] and the virial equation of state from [18].

The films of surfactants decrease the roughness of the sea surface as a result of the suppression of short wind waves, which leads to a decrease in the coefficient of resistance of the sea surface and the coefficient of turbulent heat exchange. The influence of waves on the parameters of the wind flow is determined by the parameter of wind–wave coupling, which is an increasing function of the wind strength. For light winds (when the effect of the films on waves is maximum), the relative decrement of the coefficient of resistance caused by the films is small because waves are responsible only for a small fraction of friction stresses. For strong winds, despite high values of the parameter of wind–wave coupling, the effect of films becomes weaker because the increment of growth of waves (quadratic as a function of the wind velocity) is much higher than the level of viscous dissipation. The maximum influence of the films on the coefficients of exchange is attained for $U \sim 10$ m/s, and the corresponding relative decrements of the coefficients of resistance and turbulent heat exchange are -15 and -9%, respectively. It should be emphasized that the numerical analysis of the effect of surfactants on waves in the presence of strong winds have a somewhat hypothetical character because, in this case, the films suffer intense destruction caused by the breaking of waves. However, at present, there is no quantitative description of the influence of these processes on the viscous damping decrement.

The mean-square slopes of waves for the clean sea surface and slicks obtained in the model are in satisfactory agreement with the data presented in [23]. In both cases, the model values are somewhat higher than the data of observations. The model does not confirm the phenomenon of strengthening of wind over the zone of smoothing (slick) on the sea surface described in [24]. The analysis of the behaviour of the wind velocity at a height of 5 m over the slick relative to its background value (for a given wind at a height of 10 m) reveals a small increment of the wind velocity. However, the quantity $\Delta U(5)/U(5)$ does not exceed 0.5% and can be regarded as insignificant. Even for a relatively small elasticity modulus of the film, $E = 5$ dyne/cm, viscous dissipation significantly increases (as compared with the clean surface) and, as a result, the waves shorter than 2.5 cm cannot be directly generated by the wind. The ratio of the spectral level of the wind ripple in the slick to the background level has a local minimum within the range $k = 250$–550 rad/min. This means that millimeter waves are suppressed by the films less efficiently than centimeter waves, since they are generated not by the wind but as "parasitic" capillaries on the crests of steep gravitational waves. If we take into account the solubility of the film, then the viscous decrement becomes much lower and, hence, the contrast of the energy of ripple in the slick for the same modulus of static elasticity decreases.

The authors express their deep gratitude to S. A. Ermakov for consultations and interest to their work. The present work was financially supported by the INTAS (Grants Nos. 96-1665 and 96-1817).

REFERENCES

1. Deitz, R. S. and La Fond, E. C. Natural slicks on the ocean. *J. Mar. Res.* (1950) **9**, 69–76.
2. Lucassen-Reynders, E. H. and Lucassen, J. Properties of capillary waves. *Adv. Colloid Interface Sci.* (1969) **2**, 347–395.
3. Cini, R. and Lombardidni, P. P. Damping effects of monolayers on surface wave motion in liquid. *J. Colloid Interface Sci.* (1978) **65**, No. 2, 387–389.
4. Levich, V.G. *Physicochemical Hydrodynamics.* Moscow: Izd. Akad. Nauk SSSR (1952).
5. Bass, F. G. and Fuks, I. M. *Scattering of Waves on Statistically Irregular Surfaces.* Moscow: Nauka (1972).
6. Makin, V. K., Kudryavtsev, V. N., and Mastenbroek, C. Drag of the sea surface. *Bound.-Layer Met.* (1995) **73**, 159–182.
7. Makin, V. K. and Kudryavtsev, V.N. Coupled sea surface atmosphere model. Part 1. Wind over waves coupling. KNMI MEMO WM-97-11 (1997). *Subm. to J. Geophys. Res.*
8. Kudryavtsev, V. N., Makin, V. K., and Chapron, B. Coupled sea surface atmosphere model. Part 1. Spectrum of short wind waves. KNMI MEMO WM-97-10 (1997). *Subm. to J. Geophys. Res.*
9. Ermakov, S. A., Salashin, S. G., and Panchenko, A. R. Film slicks on the sea surface and some mechanisms of their formation. *Dyn. Atmosph. Ocean.* (1992) **16**, 279–304.
10. Kudryavtsev, V. N. Physical model of the capillary-gravitational zone of the waves spectrum. *Morsk. Gidrofiz. Zh.* (1996) No. 2, 3–14.
11. Donelan, M. A. and Pierson, W. J. Radar scattering and equilibrium range in wind-generated waves with application to scatterometry. *J. Geophys. Res.* (1987) **92**, 4971–5029.
12. Ermakov, S. A., Ruvinsky, K. D., Salashin, S. G., *et al. Experimental study of the generation of capillary-gravitational ripple by strongly nonlinear waves on the surface of a deep liquid.* Gorky: (1985) (Preprint / Inst. Appl. Phys., Acad. Sci. of the USSR).
13. Donelan, M. A., Hamilton, J., and Hui, W. H. Directional spectra of wind-generated waves. *Phil. Trans. R. Soc.* London. (1985) **A315**, 509–562.
14. Plant, W. J. A relation between wind stress and wave slope. *J. Geophys. Res.* (1982) **87**, 1961–1967.
15. Makin, V. K. A note on wind speed and sea state dependence of the heat exchange coefficient. *Bound.-Layer Met.* (1998) (accepted).
16. Dyer, A. J. A review of flux-profile relationships. *Bound.-Layer Meteor.* (1974) **7**, 363–372.
17. Fernandez, D. M., Vesecky, J. F., Napolitano, D. J., Khuri-Yakub, B. T., and Mann, J. A. Computation of ripple wave parameters: A comparison of methods. *J. Geophys. Res.* (1992) **97**, C4, 5207–5213.

18. Barger, W. R. and Means, J. C. Clues to the structure of marine organic materials from the study of physical properties of surface films. In: Sigleo, A.C. and Hattori, A. (Eds.), *Marine and Estuarine Geochemistry.* Chelsea (Mich.): Lewis (1985), pp. 44–67.
19. Frew, N. M. and Nelson, R. K. Scaling of marine microlayer film surface pressure-area isotherms using chemical attributes. *J. Geophys. Res.* (1992) **97**, C4, 5291–5300.
20. Phillips, O. M. *The Dynamics of the Upper Ocean.* Cambridge: University Press (1966).
21. Large. W. G. and Pond, S. Sensible and latent heat flux measurements over the ocean. *J. Phys. Oceanogr.* (1982) **12**, 464–482.
22. Wu, J. Wind stress coefficients over sea surface from breeze to hurricane. *J. Geophys. Res.* (1982) **87**, 9704–9706.
23. Cox, C. and Munk, W. Slopes of the sea surface deduced from the photographs of sun glitter. *Bull. of the Scripps Inst. of Oceanogr., La Jolla Univ. of Calif.*, (1956) **6**, No. 9, 401–488.
24. Ermakov, S. A., Zujkova, E. M., Panchenko, A. R., Salashin, S. G., Talipova, T. G., and Titov, V. I. Surface film effect on short wind waves. *Dyn. Atmosph. Ocean.* (1986) **10**, 31–50.