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Redistribution of momentum fluxes on the water–air interface*

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Abstract — We present the results of investigation of the transformation of a momentum flux coming from the atmosphere into a water reservoir and establish the relationship between the surface velocity of the drift current and the dynamic velocity of wind. For the initial stage of the development of wind waves, we propose a dependence that enables one to determine the momentum flux spent for an increase in the intensity of waves via the momentum flux coming into the water reservoir from the wind. The behavior of the ratio of the momentum flux spent for the increase in the intensity of waves to the total momentum flux coming from the atmosphere into the water is studied depending on the dimensionless fetch and age of waves. In our analysis, we used both our own experimental data and the data available from the scientific literature.

The water–air interface is one of the most complicated, interesting, and significant boundary layers existing in nature. One of the main problems encountered in the study of this layer is connected with the analysis of energy exchange in the system of winds and waves in various stages of the development of the latter. This is clear because the interaction of winds and waves is one of the most important parts of the general problem of interaction between the hydrosphere and atmosphere. The water–air boundary layer also plays an important role in the ecological processes. Thus, the main mechanisms of self-cleaning removing various types of impurities from the water surface and cleaning the near-water air flow from gaseous and suspended impurities by filtering them and transforming into the bottom sediments are realized in this layer.

In the present work, on the basis of own experimental data and the data presented in [1–11], we study some characteristics of energy exchange accompanying the process of interaction of wind with waves. We consider the initial stage of wind-induced waves when they move with velocities much lower than the mean wind velocity at the level of wave roughness, i.e., when the age of waves $c/u_{*a} \sim 1$, where c is the phase velocity of the energy-carrying component of wind-induced waves and u_{*a} is the dynamic velocity or the velocity of friction of the wind flow.

Our experiments were carried out in the hydroaerochannel of the Hydrophysical Laboratory at the Moscow State University [8, 12]. In the course of the tests, for various wind-wave modes, at a distance of 12 m from the entrance of the wind flow in the hydroaerochannel, we measured vertical profiles of the velocities of wind and drift current. The age of waves $c/u_{*a} = c^+$ and dimensionless fetch $x_g u_{*a}^{-2} = x^+$

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varied within the ranges 0.6–2.5 and 50–2500, respectively. The measurements were carried out in a 50-cm layer of air and a 10-cm layer of water near the interface. In air, we used hot-wire anemometers and nonstandard vane anemometers as measuring devices. For the determination of the vertical profiles of velocity in water, we used thermohydrometers and calibrated balls made of polystyrene with very small positive or neutral buoyancy [2, 9, 10]. The positions of balls-indicators were recorded photographically.

According to the existing concepts [10–12], the profiles of the mean velocities of the air flow over the water surface $u_a(z)$ and the drift current $u_{\mathrm{dr}}(z)$ are described by the following logarithmic dependences:

$$u_a(z) = u_s + \frac{u_{*a}}{\kappa} \ln \frac{z}{z_{0a}}, \tag{1}$$

$$u_{\mathrm{dr}}(z) = u_s - \frac{u_{*\mathrm{dr}}}{\kappa} \ln \frac{z}{z_{0\mathrm{dr}}}, \tag{2}$$

where u_s is the surface velocity, κ is the Carman constant, u_{*a} and z_{0a} are, respectively, the friction velocity and a parameter of roughness of the wind flow, and $u_{*\mathrm{dr}}$ and $z_{0\mathrm{dr}}$ are the same characteristics of the drift current. Relations (1) and (2) well agree with the data used in the present work.

By using relations (1) and (2), we can easily find the dynamic velocities in air u_{*a} and in water $u_{*\mathrm{dr}}$ as follows:

$$u_{*a} = \kappa \frac{u_a(z_2) - u_a(z_1)}{\ln(z_2 z_1^{-1})} \quad \text{and} \quad u_{*\mathrm{dr}} = \kappa \frac{u_{\mathrm{dr}}(z_2) - u_{\mathrm{dr}}(z_1)}{\ln(z_2 z_1^{-1})}$$

(the z-axis is directed upward in air and downward in water from the boundary of the media).

The surface velocity u_s is an unknown parameter appearing in relations (1) and (2). According to [13], to find this parameter, we use the relation

$$u_s = 0.55\, u_{*a}. \tag{3}$$

Dependence (3) was obtained by different researchers and is in good agreement with the data used in the present work (see Fig. 1, where symbols of various types mark the data of laboratory tests obtained by different authors).

As a rule, the process of energy exchange between the atmosphere and wind waves is characterized by the momentum and energy fluxes. The momentum flux τ_a coming from the atmosphere into a water reservoir is spent for the formation of the drift current τ_{dr} and the growth of waves τ_w: $\tau_a = \tau_w + \tau_{\mathrm{dr}}$.

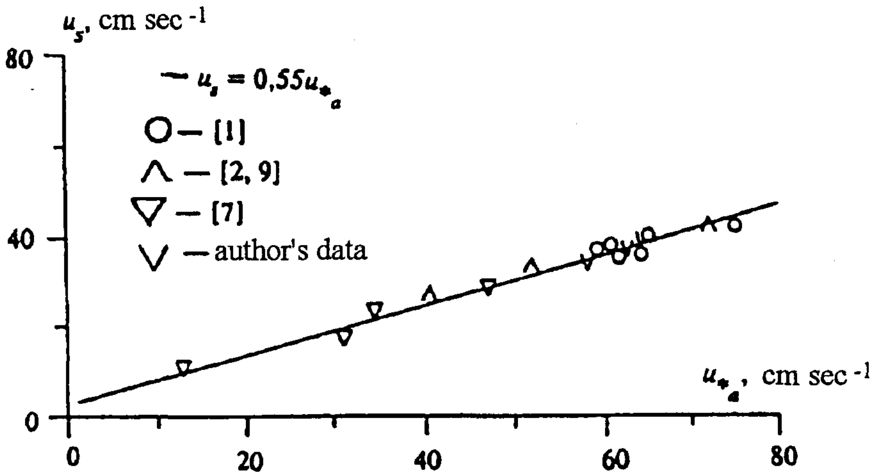

Figure 1. Comparison of the dynamic velocity of wind flow with the surface velocity of the corresponding drift current according to the data of direct measurements.

The quantities τ_a and τ_{dr} can be expressed via the dynamic wind velocity u_{*a} and the velocity of drift current u_{*dr}, respectively,

$$\tau_a = \rho_a u_{*a}^2 \quad \text{and} \quad \tau_{dr} = \rho_w u_{*dr}^2, \tag{4}$$

where ρ_a and ρ_w are the densities of air and water.

In the initial stage of generation of waves (prior to the time of their appearance), the total flux τ_a is used for the formation of currents. The fact that the appearance of the drift current precedes the generation of waves can readily be detected in the course of visual observations of the formation of wind waves in the hydroaerochannel and is confirmed in [14–17]. The term τ_w appears only at the time of generation of waves.

On the basis of the data of simultaneous measurements of vertical distributions of the velocities of wind and drift current, we can establish the relationship between the dynamic velocities of the wind flow and the corresponding drift flow (Fig. 2). It is easy to see that the dynamic velocities of the wind flow and drift current satisfy the following linear relation:

$$u_{*dr} = A\, u_{*a}. \tag{5}$$

The data presented in Fig. 2 and processed by the least-square method enable us to conclude that $A = 0.029$. Dependence (5) is depicted in Fig. 2 by the solid line. By using this dependence, one can easily determine the fraction of the momentum flux coming from air and spent for the development of the drift current as

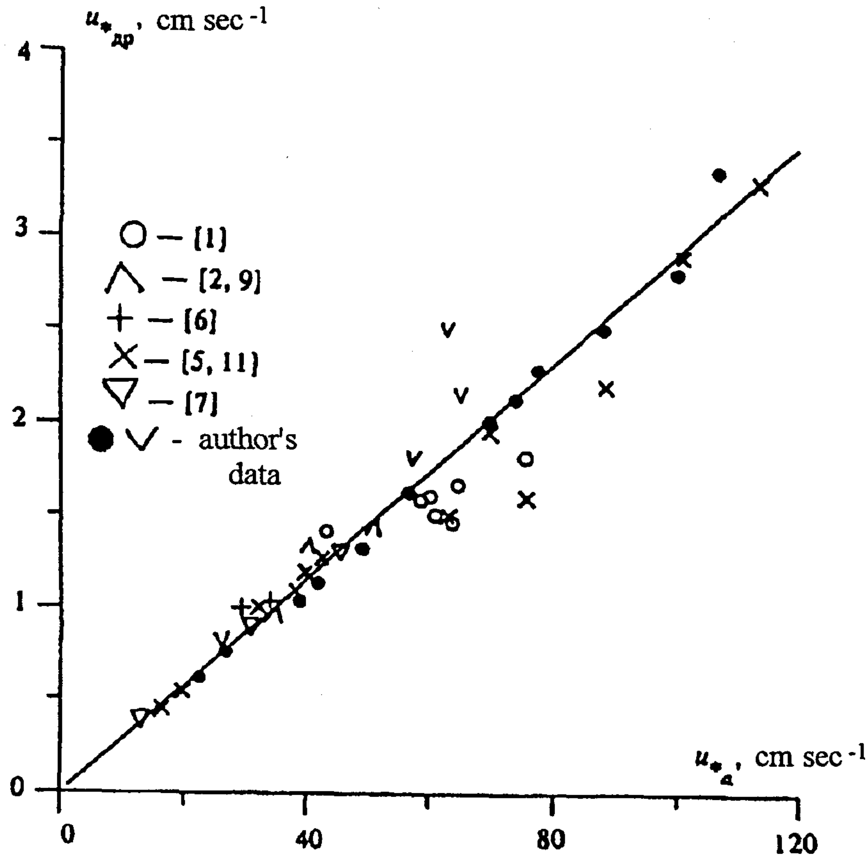

Figure 2. Relationship between the dynamic velocities of the wind flow and the corresponding drift current according to the experimental data.

$$\rho_w u_{*\text{dr}}^2 = A' \rho_a u_{*a}^2, \quad A' = 0.69.$$

Therefore, on the average, for the considered range of ages of wind waves, about 31% of the momentum flux $\rho_a u_{*a}^2$ coming from the atmosphere into the water reservoir is spent for the growth of these waves.

The experimental estimates of τ_w/τ_a were obtained by different researchers. In the major part of works, it is stated that the ratio τ_w/τ_a decreases as the age of waves c^+ and/or dimensionless fetch x^+ increase in the stages of developing or fully developed seas [17]. In the general case, the dependences of τ_w/τ_a on the dimensionless fetch x^+ and the age of waves c^+ in the stage of developing seas take the form

$$\frac{\tau_w}{\tau_a} = c_1 (x^+)^{\alpha_1}.$$

$$\frac{\tau_w}{\tau_a} = c_2 (c^+)^{\alpha_2}.$$

The values of the parameters c_1, c_2, α_1, and α_2 obtained by different authors are characterized by a great spread, which can possibly be explained by different approaches used in calculating the ratio τ_w/τ_a and the fact that, in some works, the authors deal with the stage of developing seas and, in the other works, with the stage of fully developed seas. However, it also seems probable that the dependence of the ratio τ_w/τ_a on the dimensionless fetch and the age of waves is not so primitive as indicated. Thus, in [18], the following dependence is proposed:

$$\frac{\tau_w}{\tau_a} = 32\overline{\nabla\zeta^2}, \tag{6}$$

where $\overline{\nabla\zeta^2}$ is the mean square slope of the wave surface in the direction of the wind velocity. Relation (6) satisfactorily describes the behavior of τ_w/τ_a as a function of u_{*a} in the stage of development of wind waves. Numerical calculations performed according to this formula show that, under laboratory conditions, for $x^+ = 10^2$–10^3, the ratio τ_w/τ_a takes its maximum possible values of about 0.9. As x^+ increases further, the ratio τ_w/τ_a decreases.

The data obtained in some laboratory experiments (see [18]) confirm the ratio τ_w/τ_a increases in the initial stage of development of waves. In [19, 20], one can find the data on the behavior of the dynamic velocity in water as a function of the wind velocity and fetch varying within the ranges 4.2–7.7 m sec^{-1} and 3–9 m, respectively. It is experimentally observed that the dynamic velocity in water $u_{*\mathrm{dr}}$ and, hence, τ_{dr} decrease as the fetch increases for fixed τ_a. This means that the fraction of the momentum flux τ_w coming to waves increases.

It is of interest to establish the dependence of the fraction of the momentum flux spent for the development of waves on their age c^+ and dimensionless fetch x^+ within the period of initiation of wind waves.

To solve this problem, we used the results of laboratory tests because, in this case, they are more reliable and available.

By using the profiles of wind and drift current plotted on the coordinates $u - \ln z$, we determined the dynamic velocities in air and in water (u_{*a} and $u_{*\mathrm{dr}}$). This enabled us to compute the momentum fluxes $\tau_a = \rho_a u_{*a}^2$, $\tau_{\mathrm{dr}} = \rho_w u_{*\mathrm{dr}}^2$, and $\tau_w = \tau_a - \tau_{\mathrm{dr}}$ for some values of c^+ and x^+.

In the stage of initiation of wind waves ($c^+ \le 1$ and $x^+ \le 250$), the fraction of the momentum flux spent for the growth of waves is an increasing function of c^+ and

x^+ taking values of about 0.5 for $c^+ = 1$ and $x^+ = 250$. As c^+ and x^+ increase further, the ratio τ_w/τ_a decreases and approaches ~ 0.3.

To understand the results obtained in the present work, we analyze the behavior of dynamic roughness typical of the drift current within the range $x^+ \le 250$ (Fig. 3). It is easy to see that the quantity $z_{0\mathrm{dr}}$ abruptly decreases as x^+ approaches 250 and remains practically constant as x^+ increases beyond this value.

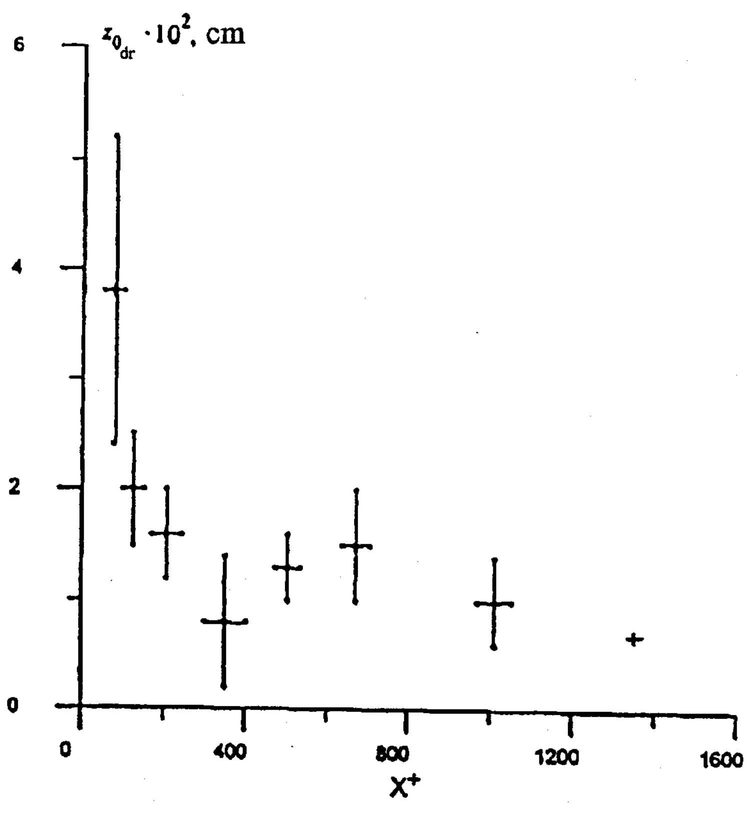

Figure 3. Dependence of the parameter of dynamic roughness $z_{0\mathrm{dr}}$ typical of the drift current on the dimensionless fetch x^+.

It seems likely that our results can be explained by changes in the shape of the wave surface in the process of development of wind waves. It is worth noting that the shape of the boundary separating the media must be different on the sides of water and air.

Thus, on the basis of the results of our investigations, we demonstrated that, in the initial stage of development of wind waves, about 30% of the momentum flux coming from the atmosphere into the water reservoir was spent for their growth. It was also discovered that, at the onset of the phase of initiation of wind waves, the fraction of momentum flux (τ_w/τ_a) spent for the development of waves increased with the age of waves and dimensionless fetch. As c^+ and x^+ increase further, the fraction of the momentum flux spent for the development of waves decreases and approaches a constant value. It seems likely that this type of behavior of the ratio τ_w/τ_a is determined by changes in the shape of the water–air interface.

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