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Laboratory investigation and direct numerical simulation of wind effect on steep surface waves

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The small scale ocean–atmosphere interaction at the water–air interface is one of the most important factors determining the processes of heat, mass, and energy exchange in the boundary layers of both geospheres. Another important aspect of the air-sea interaction is excitation of surface waves. One of the most debated open questions of wave modeling is concerned with the wind input in the wave field, especially for the case of steep and breaking waves.

Two physical mechanisms are suggested to describe the excitation of finite amplitude waves. The first one is based on the treatment of the wind–wave interaction in quasi-linear approximation in the frameworks of semi-empirical models of turbulence of the low atmospheric boundary layer. An alternative mechanism is associated with separation of wind flow at the crests of the surface waves. The "separating" and "non-separating" mechanisms of wave generation lead to different dependences of the wind growth rate on the wave steepness: the latter predicts a decrease in the increment with wave steepness, and the former – an increase. In this paper the mechanism of the wind-wave interaction is investigated basing on physical and numerical experiments.

In the physical experiment, turbulent airflow over waves was studied using the video-PIV method, based on the application of high-speed video photography. Alternatively to the classical PIV technique this approach provides the statistical ensembles of realizations of instantaneous velocity fields. Experiments were performed in a round wind–wave channel at Institute of Applied Physics, Russian Academy of Sciences. A fan generated the airflow with the centerline velocity 4 m/s. The surface waves were generated by a programmed wave-maker at the frequency of 2.5 Hz with the amplitudes of 0.65 cm, 1.4 cm, and 2 cm. The working area (27.4 $\times$ 10.7 cm2) was at a distance of 3 m from the fan. To perform the measurements of the instantaneous velocity fields, spherical polyamide particles 20 μm in diameter were injected into the airflow. The images of the illuminated particles were photographed with a digital CCD video camera at a rate of 1000 frames per second. For the each given parameters of wind and waves, a statistical ensemble of 30 movies with duration from 200 to 600 ms was obtained. Individual flow realizations manifested the typical features of flow separation, while the average vector velocity fields obtained by the phase averaging of the individual vector fields were smooth and slightly asymmetrical, with the minimum of the horizontal velocity near the water surface shifted to the leeward side of the wave profile, but do not demonstrate the features of flow separation. The wave-induced pressure perturbations, averaged over the turbulent fluctuations, were retrieved from the measured velocity fields, using the Reynolds equations. It ensures sufficient accuracy for study of the dependence of the wave increment on the wave amplitude. The dependences of the wave growth rate on the wave steepness are weakly decreasing, serving as indirect proof of the non-separated character of flow over waves.

Also direct numerical simulation of the airflow over finite amplitude periodic surface wave was performed. In the experiments the primitive 3-dimensional fluid mechanics equations were solved in the airflow over curved water boundary for the following parameters: the Reynolds number Re=15000, the wave steepness ka=0-0.2, the parameter c/u*=0-10 (where u* is the friction velocity and c is the wave celerity). Similar to the physical experiment the instant realizations of the velocity field demonstrate flow separation at the crests of the waves, but the ensemble averaged velocity fields had typical structures similar to those excising in shear flows near critical levels, where the phase velocity of the disturbance coincides with the flow velocity. The wind growth rate determined by the ensemble averaged wave-induced pressure component in phase of the wave slope was retrieved from the DNS results. Similar to the physical experiment the wave growth rate weakly decreased with the wave steepness.

The results of physical and numerical experiments were compared with the calculations within the theoretical model of a turbulent boundary layer based on the system of Reynolds equations with the first-order closing hypothesis. Within the model the wind-wave interaction is considered within the quasi-linear approximation and the mean airflow over waves within the model is treated as a non-separated. The calculations within the model represents well profiles of the mean wind velocity, turbulent stress, amplitude and phase of the main harmonics of the wave-induced velocity components and also wave-induced pressure fluctuations and wind wave growth rate obtained both in the physical experiment and DNS.

Applicability of the non-separating quasi-linear theory for description of average fields in the airflow over steep and even breaking waves, when the effect of separation is manifested in the instantaneous flow images, can possibly be explained qualitatively by the strongly non-stationary character of the separation process with the typical time being much less than the wave period, and by the small scale of flow heterogeneity in the area of separation. In such a situation small-scale vortices produced within the separation bubble affect the mean flow and wind-induced disturbances as eddy viscosity. Then, the flow turbulence affects the averaged fields as a very viscous fluid, where the effective Reynolds number for the average fields determined by the eddy viscosity was small even for steep waves. It follows from this assumption that strongly nonlinear effects, such as flow separations should not be expected in the flow averaged over turbulent fluctuations, and the main harmonics of the wave-induced disturbances of the averaged flow, which determine the energy flux to surface waves, can be described in the weakly-nonlinear approximation.

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