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Investigation of statistical parameters of turbulent air flow over waved water surface by direct numerical simulation

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Interaction of the wind flow with surface wave is one of the central questions in the wave modeling. Of special interest is the case of steep waves, when the strongly non-linear effects (e.g. sheltering, flow separation, vortex formation etc.) can be expected in the airflow over waves. In this paper the detailed structure and statistical characteristics of a turbulent atmospheric boundary layer over waved water surface is studied by direct numerical simulation (DNS). In the experiments two-dimensional water waves with different wave age parameters (c/u*=0-10, where u* is the friction velocity and c is the wave celerity), wave slope ka=0-0.2 and at a bulk Reynolds number Re = 15000 were considered. The shape of the water wave is prescribed and does not evolve under the action of the wind. The numerical algorithm is similar to the one employed by Sullivan et al. (2000), but is adjusted for a staggered grid. The full, 3D Navier-Stokes equations are solved in curvilinear coordinates in a frame of reference moving the phase velocity of the wave. The shear driving the flow is created by an upper plane boundary moving horizontally with a bulk velocity in the x-direction. Periodic boundary conditions are considered in the horizontal (x) and lateral (y) directions, and no-slip boundary condition is considered in the vertical z-direction. The grid of nodes in the x, y, and z directions is used. The Adams-Bashforth method is employed to advance the integration in time and the equation for the pressure is solved iteratively by using FFT in the x and y directions and the Gauss method in the z-direction. In the present study, all the computations were carried out for 12000 time steps, which is 200 dimensionless large-scale time units (based on the bulk velocity and the wave length) and each time unit is typically about 20 viscous time units [ ]. Ensemble-averaged velocity and pressure fields were evaluated from 500 instantaneous flow-field data samples which covered the time period of 100 large-scale time units. Profiles of the mean velocity and turbulent stresses were obtained by averaging over wavelength.

Instantaneous vector velocity fields manifested considerable airflow separation at the crests of the surface waves similar to that observed in physical experiments by PIV-technique. Alternatively the ensemble averaged velocity fields were non-separating and had typical structures similar to those excisting in shear flows near critical levels, where the phase velocity of the disturbance coincides with the flow velocity.

The results of the measurements were compared with the calculations within the theoretical model of a turbulent boundary layer, based on the system of Reynolds-averaged equations with the first-order closure hypothesis. The wind-wave interaction is considered within the quasi-linear approximation, i.e. wave-induced disturbances in the air flow are considered in the linear approximation, but the resistive effect of the wave momentum flux on the mean flow velocity profile is taken into account. The mean airflow over waves within the model is treated as a non-separated one. Mean wind velocity and turbulent stress profiles, amplitude and phase of the main harmonics of the wave-induced velocity components and also wave-induced pressure fluctuations and wind-wave growth rate calculated within the quasi-linear model are in good agreement with the results of DNS.

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