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The study of the properties of turbulent stably stratified air flow over water surface by direct numerical simulation

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Parameterization of turbulent momentum and heat fluxes in a turbulent, stably stratified boundary layer flow over water surface is important for numerical climate modeling and weather prediction. In this work, the detailed structure and statistical characteristics of a turbulent, stably stratified atmospheric boundary layer flow over water surface is studied by direct numerical simulation (DNS). The most difficult case for modeling is that of flows at high Reynolds numbers and sufficiently steep surface waves, when strongly non-linear effects (e.g. sheltering, boundary layer separation, vortex formation etc.) are encountered. Of special interest is the influence of the wind flow stratification on the properties of boundary-layer turbulence and the turbulent momentum and heat fluxes. In DNS a two-dimensional water wave with different wave age parameters (c/u*, where u* is the friction velocity and c is the wave celerity), wave slope ka varying from 0 to 0.2 and bulk Reynolds number Re (from 15000 to 80000) and different Richardson numbers are considered. The shape of the water wave is prescribed and does not evolve under the action of the wind. The full, 3D Navier-Stokes equations under the Boussinesq approximation 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 360 x 240 x 360 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. Ensemble-averaged velocity and pressure fields are evaluated by averaging over time and the spanwise coordinate. Profiles of the mean velocity and turbulent stresses are obtained by averaging over wavelength.
The DNS results show that the properties of the boundary layer flow are significantly affected by stratification. If the Richardson number Ri is sufficiently small, the flow remains turbulent and qualitatively similar to the non-stratified case. On the other hand, at high Ri turbulent fluctuations and momentum and heat fluxes decay to zero at low wave slope but remain finite at sufficiently large ka (>0.15). Parameterization of turbulent and heat production, diffusion and dissipation is also performed by a closure procedure and compared with the results of DNS. The criteria in terms of the product of the Kolmogorov time scale and local buoyancy frequency or/and the ratio of the Kolmogorov vs. Ozmidov lengh scales is proposed to characterize the different flow regimes observed in DNS.

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