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# The study of the effect of the surface wave on turbulent stably-stratified boundary layer air-flow by direct numerical simulation

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Detailed knowledge of the interaction of surface water waves with the wind flow is of primary importance for correct parameterization of turbulent momentum and heat fluxes which define the energy and momentum transfer between the atmosphere and hydrosphere. The objective of the present study is to investigate the properties of the stably stratified turbulent boundary-layer (BL) air-flow over waved water surface by direct numerical simulation (DNS) at a bulk Reynolds number varying from 15000 to 80000 and the surface-wave slope up to ka = 0.2.
The DNS results show that the BL-flow remains in the statistically stationary, turbulent regime if the Reynolds number (ReL) based on the Obukhov length scale and friction velocity is sufficiently large (ReL > 100). In this case, mean velocity and temperature vertical profiles are well predicted by log-linear asymptotic solutions following from the Monin-Obukhov similarity theory provided the velocity and temperature roughness parameters, z0U and z0T, are appropriately prescribed. Both z0U and z0T increase for larger surface-wave slope. DNS results also show that turbulent momentum and heat fluxes and turbulent velocity and temperature fluctuations are increased for larger wave slope (ka) whereas the mean velocity and temperature derivatives remain practically the same for different ka. Thus, we conclude that the source of turbulence enhancement in BL-flow are perturbations induced by the surface wave, and not the shear instability of the bulk flow.
On the other hand, if stratification is sufficiently strong, and the surface-wave slope is sufficiently small, the BL-flow over waved surface relaminarizes in the bulk of the domain. However, if the surface-wave slope exceeds a threshold value, the velocity and temperature fluctuations remain finite in the vicinity of the critical-layer level, where the surface-wave phase velocity coincides with the mean flow velocity. We call this new stably-stratified BL-flow regime observed in our DNS a “wave-pumping” regime. We develop a theoretical model and explain the occurrence of the wave-pumping regime observed in DNS as a result of the generation of two-dimensional (2D) disturbances in the air flow under the influence of the surface wave and secondary, parametric instability of these disturbances along the surface-wave front direction. The model predicts that the wave-pumping regime occurs only for sufficiently steep waves which is in agreement with DNS results. The model prediction for the amplitudes of the wave-induced 2D disturbances in the air flow is also in good qualitative and quantitative agreement with DNS results. The results also show that increasing the bulk Reynolds number of the air-flow leads to the development of a wide spectrum of the disturbances. At a sufficiently high super-criticality we expect a transition to occur from the wave-pumping regime to a fully-developed, turbulent BL-flow regime, even at high Richardson number when the air flow over a smooth surface relaminarizes.

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