Wind turbulence over surface water waves in strongly forced conditions

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Accurate predictions of the mean wind profile and the air–sea momentum flux require a thorough understanding of the wave boundary layer turbulence over surface waves. A set of momentum and energy equations is derived to formulate and analyze wave boundary layer turbulence. The equations are written in wave-following coordinates, and all variables are decomposed into horizontal mean, wave fluctuation, and turbulent fluctuation. The formulation defines the wave-induced stress as a sum of the wave fluctuation stress (because of the fluctuating velocity components) and a pressure stress (pressure acting on a tilted surface). The formulations can be constructed with different choices of mapping. Next, a large-eddy simulation result for wind over a sinusoidal wave train under a strongly forced condition is analyzed using the proposed formulation. The result clarifies how surface waves increase the effective roughness length and the drag coefficient. Specifically, the enhanced wave-induced stress close to the water surface reduces the turbulent stress (satisfying the momentum budget). The reduced turbulent stress is correlated with the reduced viscous dissipation rate of the turbulent kinetic energy. The latter is balanced by the reduced mean wind shear (satisfying the energy budget), which causes the equivalent surface roughness to increase. Interestingly, there is a small region farther above where the turbulent stress, dissipation rate, and mean wind shear are all enhanced, possibly due to transient airflow separation.