Air-sea momentum flux and normalized roughness length over breaking and nonbreaking surface waves

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Waves on the sea surface act as roughness elements on the marine boundary layer. One of the unique features of this roughness sublayer is that the roughness elements and the flow within the roughness sublayer form a coupled dynamical system. We develop a coupled wind-wave model that includes the form drag of both breaking and nonbreaking waves. Above the air-sea interface, within the constant stress layer, the momentum flux partitions into turbulent, wave-induced (by nonbreaking waves) and breaking wave components. Ahead of a breaking crest the airflow separates, causing a pressure drop on the leeside of the wave. This pressure drop leads to energy and momentum fluxes from wind to breaking waves, while reducing the turbulent stress in the air. By conserving both energy and momentum in the wave boundary layer and also imposing the wave action balance, we derive coupled equations governing the turbulent stress, wind speed, wave saturation spectrum, and breaking wave statistics (total breaking crest length per unit surface area as a function of wavenumber). Furthermore, we assume that smaller scale waves are sheltered from wind forcing if they are in airflow separation regions of longer breaking waves (spatial sheltering effect). The model results yield the equivalent roughness length and the Charnock coefficient in different wind and wave conditions. When breaking waves dominate the form drag over very young seas, the roughness length is related to the height of the largest breaking waves. When nonbreaking waves dominate, waves of all scales (entire wave spectrum) contribute to the momentum flux.