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Spatial and statistical analysis of coherent vortical structures within a stress-driven free-surface turbulent shear flow

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The water surface under high wind condition is characterized by elongated high-speed streaks and randomly emerged low-speed streaks, which are attributed to underneath coherent vortical motions. These vortical structures within aqueous turbulent boundary layer plays a critical role in turbulent exchange, their characteristics and statistics are therefore of interest in this study. Direct numerical simulation of an aqueous turbulent flow bounded by a stress-driven flat free surface was performed. Simulation results of cases with high wind condition (surface friction velocity = 1.22 cm/s) as well as weak wind condition (surface friction velocity = 0.71 cm/s) are analyzed. To identify the underlying vortical structures, an indicator of swirling strength derived from local velocity-gradient tensor is adopted. A formal classification scheme, based on the topological geometry of the vortex core, is then applied to classify the identified structures. Surface layers with the two wind conditions reveal similar results in statistics and spatial distribution of vortical structures. Two types of characteristic vortices which induce the surface streaks are extracted, including quasi-streamwise vortex and reversed horseshoe vortex (head pointing upstream), most inclining at about 10 to 20 degrees. Quasi-streamwise vortices are the dominant structure, and both high- and low-speed streaks are fringed with such vortices; they adjoin the surface streaks as counter-rotating arrays in either staggered or side-by-side spatial arrangement. The length of quasi-streamwise vortices, however, are significantly shorter than the corresponding surface streaks, only 10% of the extracted quasi-streamwise vortices are longer than 150 wall units. Reversed horseshoe vortices, associated with downwelling motions and surface convergence, are located beneath the high-speed streaks. In contrast to the turbulent boundary layer next to a flat wall, typical forward horseshoe vortices (head pointing downstream) associated with upwelling motions are barely found within the free-surface turbulent shear flow.

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