# PHYSICS OF FREE-SURFACE TURBULENCE AND CHALLENGES TO LARGE-EDDY SIMULATION

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## 1. Introduction

Free-surface turbulence refers to turbulent flows in the vicinity of a freely movable, two-fluid interface, the most common one being the air-water interface. The physics of free-surface turbulence is essential to many industrial and biological processes involving gas-liquid flows. It also plays an important role in pollutant transport at water surfaces, ship hydrodynamics, and remote sensing of ocean surfaces.

In the atmosphere-wave-ocean system, the interaction of turbulent wind and ocean current with surface water wave is a challenging fluid mechanics problem. The fluid motion at air-sea interface directly affects the transport process between the atmosphere and the oceans. One of the applications that receives much attention is greenhouse gases related to global warming. The oceans have an enormous capacity for the adsorption of gases. The exchange rate of these gases between the atmosphere and the oceans, which is dominated by the air-water interfacial mass transfer dynamics, is paramount in our understanding and prediction of the greenhouse effects in the atmosphere and long term climate changes.

The object of this article is to provide a brief review of the physics of free-surface turbulence. Due to the complexity of the problem, the scope of the free-surface turbulence physics discussed in this article is of a limited nature. We focus on flows encountered in air-sea interaction and interfacial transport processes, with an emphasis on features relevant to large-eddy simulation (LES). It should be noted that LES of free-surface turbulent flows is a new area of research under active development. Many of questions encountered in developing subgrid-scale (SGS) models and in the implementation of LES remain to be answered in future research. As a result, instead of trying to presenting a mature methodology, in this article we discuss challenges facing LES of free-surface turbulent flows, in hope that these issues will be resolved in the near future.

## 2. Free-surface turbulence with small surface deformation

### 2.1. Introduction

We first discuss free-surface turbulent flows with small surface deformation. Although appearing to be much simpler than those with large surface deformation including breaking waves, turbulence near an almost flat free surface possesses some unique and profound physics that need to be understood first. Such an understanding also forms a basis for further investigation of flows with large surface elevation.

We further simplify the problem by focusing on the waterside motions, because the flow on waterside often plays a dominant role, a fact that can be seen in the problem of two-phase turbulent Couette flow shown in Figure 1. In this system, the top half of the domain is air and the bottom half is water. The flow is driven by the top boundary moving at a constant speed while the bottom boundary remains stationary. Continuity of velocity and shear stress is enforced at the air-water interface.

In Figure 1, the vortical structures on the airside and waterside of the interface are represented by the iso-surface of the second largest eigenvalue of the tensor $\underline{S}^2 + \underline{\Omega}^2$, with $\underline{S}$ and $\underline{\Omega}$ being the symmetric and anti-symmetric parts of the velocity gradient $\nabla\vec{u}$, respectively (Joeng & Hussain 1995). On the air side, the vortices are mostly streamwise, and are part of hairpin vortices, resembling those in flows near a solid wall. On the waterside, however, the flow possesses many unique features unseen in boundary layer flows at a solid wall. It is found that vortical structures in the water near the interface can be characterized into four categories: hairpin vortices, quasi-streamwise vortices, and interface-attached single and paired ("U"-shape) vortices (Shen & Yue 2006). Of special interest is the evolution of a hairpin vortex with its head portion near the interface and the legs extending to the bulk flow. As the hairpin vortex approaches the interface, the head portion is dissipated, and the hairpin legs attach to the interface to evolve into interface-attached vortices. This vortex evolution process is similar to the one found in the free surface turbulence in which the airside is treated as a vacuum (Shen et al. 1999).

Figure 2 shows the velocity streaks associated with momentum transfer near the interface. On the airside, the boundary layer structure is very similar to that near a solid wall. For example, as the distance from the interface increases, the structure at the interface disappears first and becomes similar to a wall boundary layer flow. Moving away from the interface, the flow structures on the airside become much smaller than those at the interface and they change rapidly as the distance increases. On the waterside, however, the structures of streaks vary little with the distance from the interface. Such result shows that the streaks at the air-water interface are mainly controlled by the water motions. Driven by the water motion that has much more inertia, the air-side flow is quite similar to boundary layer flows with a solid wall.