

Mechanistic Investigation of Small-Scale Air-Sea Coupled Dynamics Using LES

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LONG-TERM GOAL

Our long-term objective is to understand the small-scale dynamics of coupled boundary layers air-sea transfer (CBLAST) by performing DNS and LES of both air and ocean turbulent flows with coupled free-surface boundary conditions. The primary focus and an ultimate goal is to obtain the physical foundation for the characterization and parameterization of the momentum, mass and heat transfer within the atmosphere-ocean wave boundary layer (WBL).

OBJECTIVES

The scientific and technical objectives of this project are to:

- Develop high-performance DNS/LES capabilities for the air-ocean-wave flow field at small spatial scales, with the focus on air and water turbulent motions under the influence of coupled free-surface boundary conditions
- Elucidate the statistics, structures and dynamics of air and water turbulent flows in the vicinity of the air-sea interface
- Identify and assess the key transport processes within the atmosphere-ocean WBL
- Assess, develop and validate specialized physics-based turbulence modeling for the atmosphere-ocean WBL
- Perform direct quantitative comparison and cross-validation of DNS/LES simulations with experimental/field measurements, compliment and collaborate with other modeling efforts
- Characterize and parameterize the mass, momentum and energy transfer budget in WBL for coupled air-ocean-wave boundary modeling

APPROACH

We develop a systematic approach based mainly on two complementary computational methods for the DNS and LES of coupled air and ocean turbulent flows: (i) at low wind speeds (<5 m/s), we employ a boundary interface tracking method (BITM) which utilizes coupled free-surface boundary

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conditions based on boundary-fitted meshes; and (ii) at moderate wind speeds (>5 m/s), where the waves steepen/break, we shift to using an Eulerian interface capturing method (EICM) based on a level set approach. These developments are at the cutting edge of computational free-surface hydrodynamics.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. The transport of scalars is also implemented in the BITM. At the air-water interface, linearized or fully-nonlinear free-surface coupled boundary conditions are used, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition requiring a stress balance across the interface. The governing equations are discretized using a pseudo-spectral method in the horizontal directions and a finite-difference scheme in the vertical direction. A second-order fractional step scheme is used for the time integration of the flow field and the motion of the air-water interface.

In EICM, the air and water together are treated as a system with varying density, viscosity and diffusivity. A continuous scalar, a level set function, representing the signed distance from the interface is used to identify each fluid. The fluid motions are governed by the Navier-Stokes equations while the scalar is advected with the flow governed by a Lagrangian-invariant transport equation. A large wave simulation (LWS) technique is used to model the effects of small surface wave fluctuations. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

WORK COMPLETED

Substantial progress has been made during the fiscal year of 2003. The major accomplishments include the further development of high-performance DNS and LES/LWS capabilities for air-water-wave turbulent flows that substantially improve the accuracy and physical meaning of the numerical results over existing computational approaches. The codes are optimized on high-performance parallel computing platforms to provide high-resolution results in a timely manner. As canonical problems, we have investigated coupled air-water turbulent Couette flows and unsteady spilling breaking waves. Through extensive simulations and analyses, we have gained useful insights into the structures and dynamics of turbulent flows in the vicinity of the air-sea interface, which include:

- *Detailed velocity and vorticity fields in the coupled air-water turbulent flow:* Statistical characteristics of the turbulent air-water interface have been obtained and their unique differences from the conventional wall boundary layers and shear-free (water only) surface layers are identified.
- *Coherent structures in the vicinity of the air-water interface:* Streamwise vortex structures and low-speed streaks and their roles in the near-interface transport process have been elucidated.
- *High-resolution simulation of coupled air-water flow through the wave spilling breaking process:* The detailed mechanisms of wave-turbulence interactions are investigated. In particular, we have identified the vortex flux at the surface and sources of vorticity generation during the breaking event.
- *Turbulent kinetic energy budget in the air-water coupled boundary layer:* Through an ensemble of simulations, we are able to characterize the different turbulence mechanisms operating in the respective near-surface scales for both the air and water regimes. Evolution of turbulence energy in the

air-water-wave boundary layer is illustrated. Both the inviscid and viscous transport processes associated with wave motions have been identified.

RESULTS

During the fiscal year of 2003 we performed extensive simulations for coupled air-water turbulent flows using numerical methods of BITM and EICM. Using the canonical problems of coupled air-water Couette flow and unsteady spilling breakers, we are able to separate and identify the effects of air-water viscous coupling and the effects of wave-turbulence interactions, which are essential for the development of physics-based turbulence modeling.

Representative results for the coupled air-water Couette flow are shown in Figures 1 to 3. With high-resolution simulations, we are able to obtain the detail flow structures in the air-water boundary layer. In particular, we have examined the coherent streamwise vorticity structures in the vicinity of the air-water interface (Fig. 1), the understanding of which is essential for the investigation of the transport process of mass, momentum and energy in the air-water boundary layer. A typical example is given in Fig. 2, which shows the low-speed 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, consider the left column of Fig. 2. As the distance from the interface increases (a to b to c), the structure at the interface disappears first and becomes similar to a wall-boundary layer flow. On the waterside, however, the structures of streaks vary little with depth (right column in Fig. 2). This result shows the low-speed streaks at the air-water interface (Fig. 2a) are mainly controlled by the water motions. Based on the extensive simulation datasets, we also obtained important statistics such as the turbulent kinetic energy budget in the coupled air-water boundary layer (Fig. 3).

Taking advantage of its robustness and accuracy in computing multiphase flows with complex interface deformation, we employ the EICM method to study the effects of wave-turbulence interactions. Figures 4 and 5 show the results of the spilling breaker of a progressive wave. Detailed velocity and vorticity fields are obtained for both the air and watersides of turbulent motions. It is found that the strong surface vorticity exist at the interface (Fig. 4 center). Further examination shows that there are two main sources for the generation of vorticity: surface parallel velocity at sharp changes in interface curvature (Fig. 4 left) and work due to surface tension forces (Fig. 4 right). We also analyzed the process of energy transfer at the free surface (Fig. 5 left), which is found to play a significant role in the evolution of turbulent kinetic energy in the air-water-wave boundary layer. We found that the interfacial transport process is dominated by the pressure forces. The inviscid energy transport (Fig. 5 center) has a magnitude much larger than the viscous transport (Fig. 5 right).

IMPACT/APPLICATION

This project is an essential numerical part of an overall coordinated effort involving experimentalists, air-sea modelers, and physical oceanographers. Our numerical simulations will provide detailed descriptions of the air-sea-wave boundary layer at small scales, which are critical for the cross-validation with measurement, and modeling and parameterization of transport process.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure and will be used to verify experimental databases. They also provide a framework and a physical basis for the parameterization of coupled air-ocean-wave dynamics.

RELATED PROJECTS

This project is a part of the coupled boundary layers air-sea transfer (CBLAST) program (<http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html>). Our numerical study is performed in close collaboration with experimental observations and other modeling efforts.

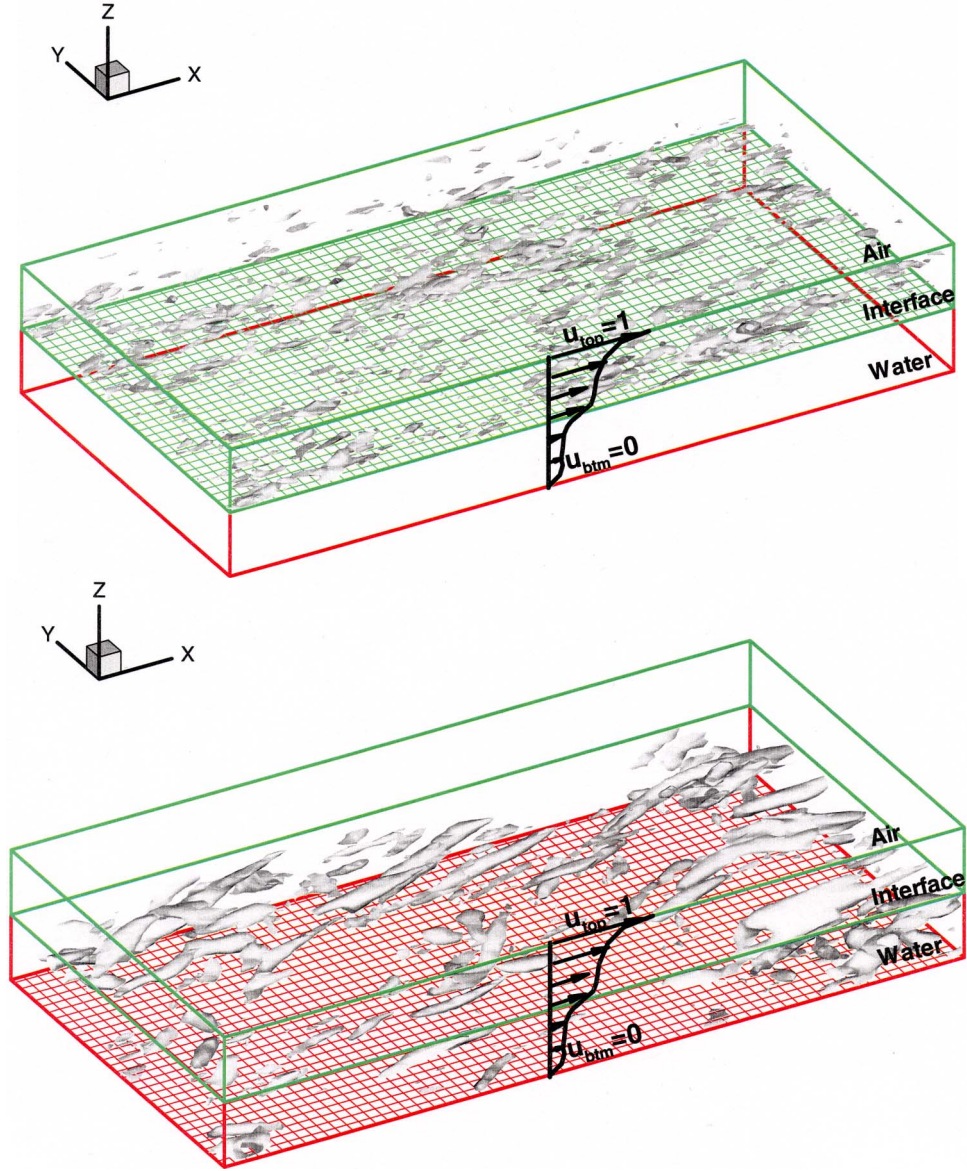


Figure 1. Air-water coupled Couette flow and the coherent streamwise vortical structures near the interface. Vortices are represented by the second largest eigenvalues of the vorticity-strain tensor. The top figure is for the airside of structures and the bottom figure is for the waterside.

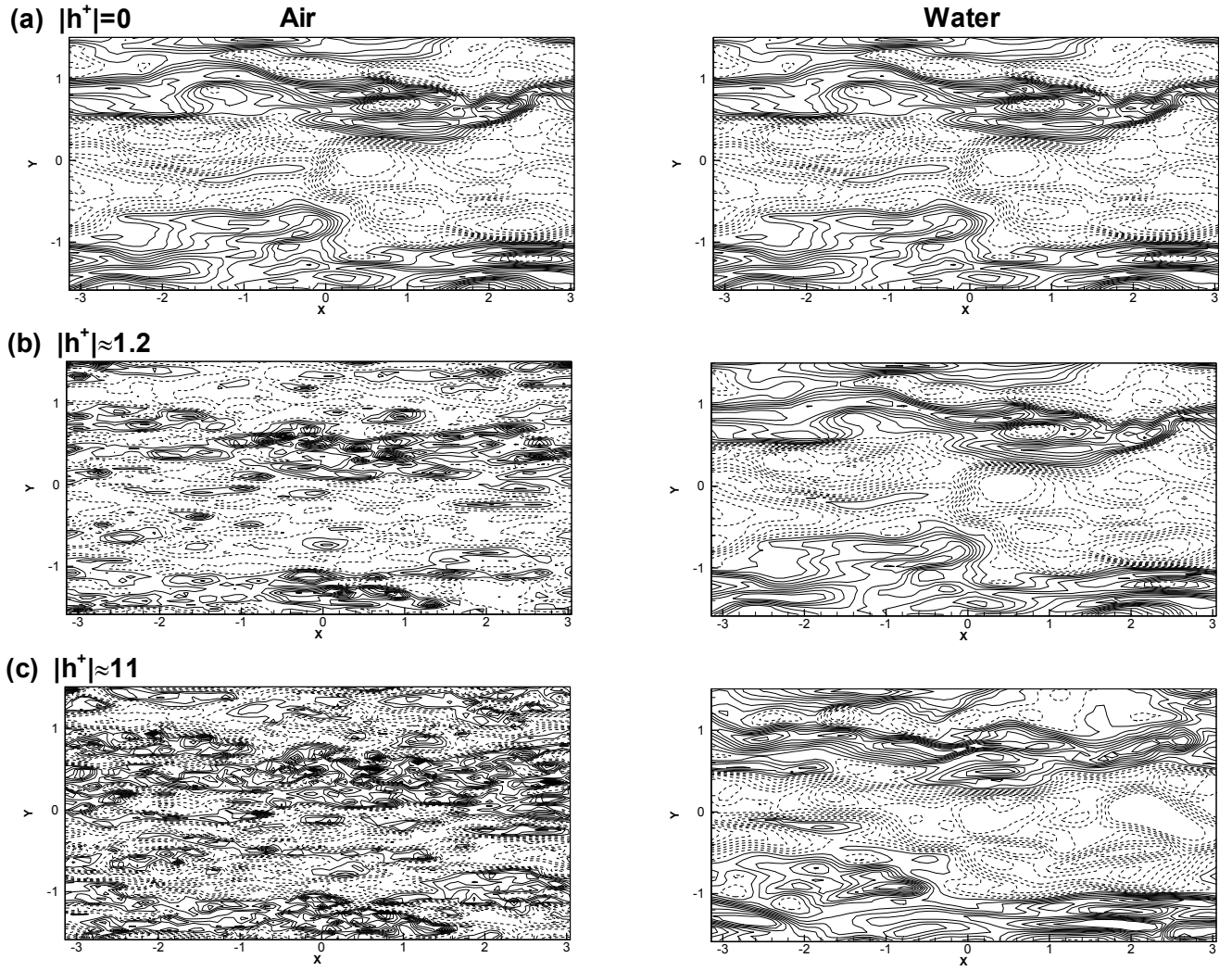


Figure 2. *Low speed streaks in the coupled air-water boundary layers at different distances from the interface. Solid and dashed contour lines respectively represent positive and negative values of streamwise component of velocity fluctuations on horizontal planes.*

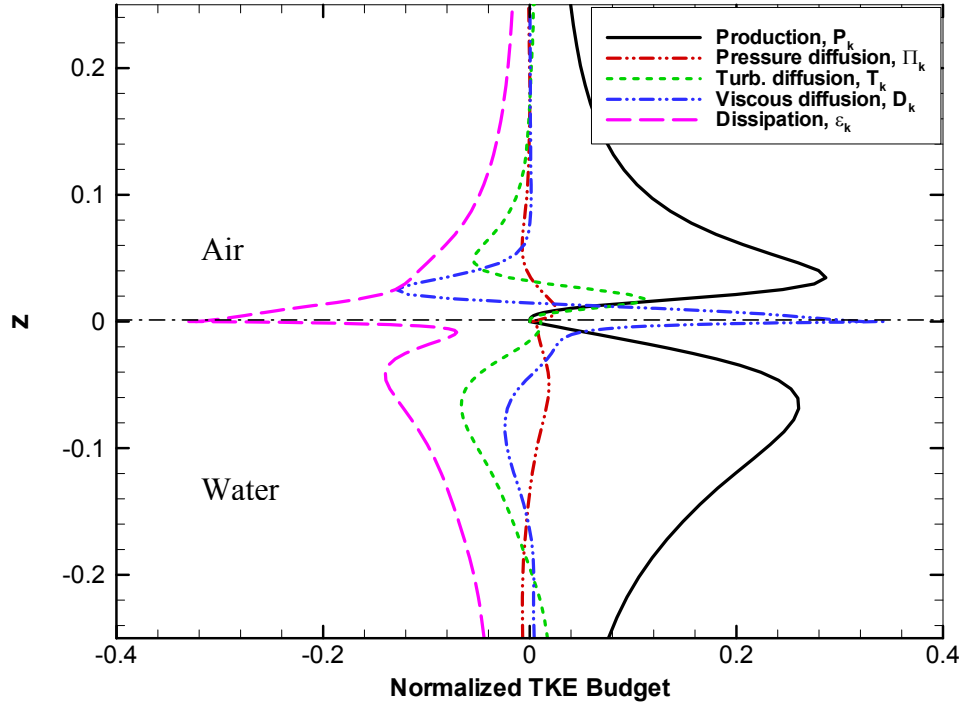


Figure 3. *Terms in the turbulence kinetic energy budget in the coupled air-water boundary layer.*

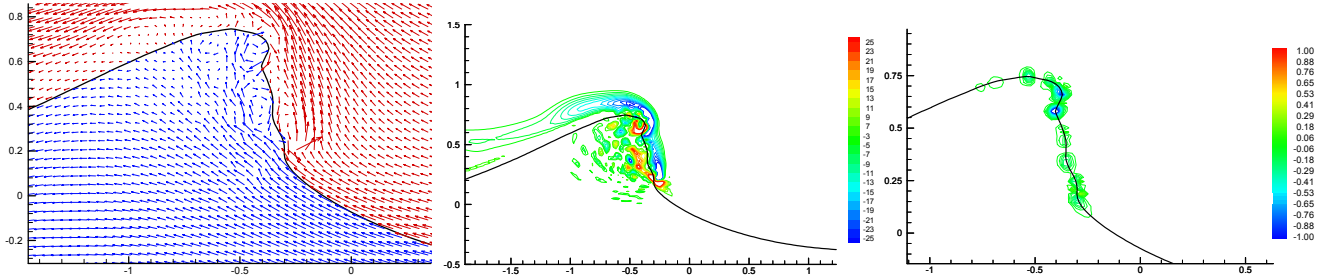


Figure 4. *Two main sources of vorticity shown for a particular instant of spilling breaking wave ($T=4.440$). Vorticity contours are shown in center. First, velocity vectors in the reference frame of the crest (left) show surface parallel velocity fails to follow sharp changes in curvature. Second, the work down by surface tension (right) has peaks at points of intense vorticity flux.*

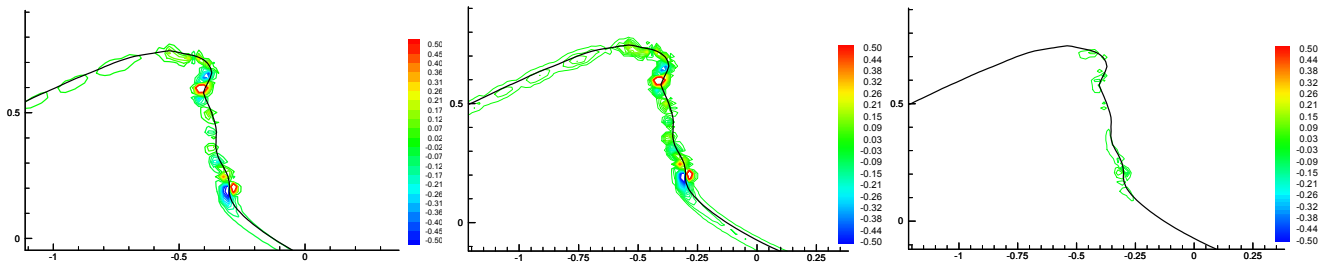


Figure 5. *Total rate of energy transfer at the interface between air and water (left). It has two components: inviscid (center) and viscous (right) energy transport. Plotted on the same scale, while the inviscid component is dominant, the viscous energy transport is non-negligible in regions such as the bulge and toe of the spilling breaking wave.*