Continued Investigation of Small-Scale Air-Sea Coupled Dynamics Using CBLAST Data

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LONG-TERM GOAL

Our long-term goal is to obtain a more thorough understanding of the dynamics of coupled boundary layers air-sea transfer (CBLAST) at relatively small spatial scales, by performing direct numerical simulation (DNS) and large-eddy simulation (LES) together with large-wave simulation (LWS) for both air and ocean turbulent flows with surface waves. 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:

- Use high-performance DNS and LES/LWS of coupled air-water wave boundary layers to fully resolve and capture the coupled air-sea-wave dynamics at ocean wave scales. Identify and assess the key transport processes within the atmosphere-ocean WBL. Elucidate the statistics, structures and dynamics of air and water turbulent flows in the vicinity of the air-sea interface.
- Provide direct comparison and cross-calibration with measurements, to help obtain physical interpretation of field data, and to develop parameterization for mass, momentum and energy transfer budget in WBL for coupled air-ocean-wave boundary modeling.
- Establish a physical basis for the characterization and parameterization of the mass, momentum and energy transfer within WBL.

APPROACH

For the DNS and LES/LWS of coupled air and ocean turbulent flows, we have developed a suite of high-performance, complementary computational methods. These include: (i) a boundary interface tracking method (BITM) for low wind speeds (<5 m/s); and (ii) an Eulerian interface capturing method (EICM) for moderate to high wind speeds (>5 m/s), where the waves steepen/break. The numerical schemes of BITM are based on boundary-fitted grids and coupled free-surface boundary conditions. The EICM is based on a level set approach. These developments are at the cutting edge of computational free-surface hydrodynamics. Transport of passive scalars in the coupled air-water flow

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system is implemented. Both the BITM and EICM codes are optimized on parallel computing platforms to provide high-resolution results in a timely manner.

The BITM method solves the incompressible Navier-Stokes equations for both air and water. Free-surface coupled boundary conditions are used at the air-water interface, with the kinematic boundary condition requiring that the interface remains a material surface, and the dynamic boundary condition specifying a stress balance across the interface. The transport of scalars is governed by a convection-diffusion equation. 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 evolution, the transport of scalars, 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 (the level set function), which represents 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 technique is used to model the effects of small surface wave fluctuations on large waves. The governing equations are discretized on an Eulerian grid using a finite-difference scheme.

WORK COMPLETED

Major progresses made during the fiscal year of 2006 include:

- Obtain extensive dataset for air-water-wave turbulent flows through systematic, large simulations; post process simulation data.
- Illustrate wave-current interaction with TKE and enstrophy in the turbulent flow being quantified.
- Identify key transport processes at the air-sea interface; illustrate effects of coherent turbulence structures on atmosphere-ocean interfacial scalar transfer.
- Complete turbulent kinetic energy (TKE) budget in the vicinity of air-sea interface to establish the physical basis of WBL modeling and parameterization.

RESULTS

During the fiscal year of 2006, significant progresses have been made towards the understanding of air-water-wave interactions. Using systematic simulations on high-performance parallel computers with finely-resolved temporal and spatial detail, we obtain a complete physical description of the turbulent air-sea flow field which fully captures air-water dynamics. This provides a basis for the identification of key transport processes within the atmosphere-ocean boundary layer. A typical result of wind-current-swell BITM simulation is shown in Figure 1. For moderate to high wave amplitude and steepness, the wave effects play an essential role in the air-sea interaction (Figure 2) and must be accounted for. For small wave magnitudes typical under low wind conditions, on the other hand, our extensive study shows that the presence of waves has a relatively minor effect on the overall flow dynamics, while the surface roughness itself can be obtained from the underlying pressure field.

In this study we are able to complete the TKE budget in atmosphere-ocean WBL. The evolution of TKE is governed by a number of processes. It is produced by the interaction between Reynolds stress and the shear in the mean flow. Meanwhile, the TKE is dissipated by viscosity. In addition to these source and sink processes, TKE is transported among different flow regions by pressure fluctuations and velocity fluctuations. At regions where the TKE varies abruptly, viscous diffusion also contributes to the TKE. Figure 3 shows our results of TKE terms at an air-sea interface with direct comparison to wall boundary layer results. It is found that the TKE production is large near the interface. The sharp decrease at the interface is caused by the reduction of Reynolds stress there. Viscous diffusion is only significant very close to the interface. Transport due to turbulence velocity fluctuations transports TKE from the bulk region of the air to the near-surface region. On the waterside, turbulence transport removes part of TKE from the near-surface region and put it at the deep region. Dissipation increases towards the interface in the air and reaches a maximum at the interface, behaving like near a solid wall. On the waterside, as the interface is approached, dissipation decreases first and then increases. The pressure transport is much smaller than other terms and it is not plotted in Figure 3. The results obtained here will allow us to develop advanced closure models needed, for example, in larger scale and coarser grid simulations such as those used in meso-scale LES and Reynolds-averaged Navier-Stokes (RANS) computations.

We have also extended the study of air-sea turbulence transport to interfacial transfer of passive scalars, which serves as a model for gas and heat transfer at ocean surfaces. The instantaneous, three-dimensional numerical data of the flow and the scalar fields provide a framework for the investigation of scalar transport dynamics and their modeling. Figure 4 shows an example of our simulation results. It is found that transport process is controlled by turbulent coherent vortical structures and fluid splat and anti-splat motions at the free surface. The contribution of each type of flow structure to the scalar transport can be quantified by a novel conditionally-averaging technique. We have also developed numerical capability for surfactant-turbulence interactions. Our simulation results show that the presence of surfactant substantially reduces local surface divergence, which is an indicator of the magnitude of splat motions. The reduction in the surface divergence is caused by restoration effects of surface-tension gradients, and is found to be responsible for the reduction of scalar transport rate at a contaminated surface.

IMPACT/APPLICATION

This study aims to obtain a fundamental understanding of the air-sea wave coupling dynamics at small scales at low wind speeds. Our work is intended as a small yet essential part of an overall coordinated effort involving field experimentalists, air-sea modelers, and physical oceanographers to obtain improved physics-based parameterizations for air-sea interactions. Our numerical simulations will provide detailed descriptions of the air-sea-wave boundary layer at small scales, and a physical basis for the modeling and parameterization of transport process within the atmosphere-ocean wave boundary layer. The simulations will also provide comparison and cross-validation with field measurements. Finally, our numerical framework can be used as a powerful tool to help the interpretation and syntheses of field data, and parameterization of WBL transport process for the coupled air-ocean WBL modeling.

TRANSITIONS

The numerical datasets obtained from this project will provide useful information on physical quantities difficult to measure. Simulations in this study will provide guidance, cross-calibrations and validations for the experiments. They also provide a framework and a physical basis for the parameterization of coupled air-ocean-wave dynamics.

RELATED PROJECTS

This project is part of the ONR-sponsored Coupled Boundary Layers Air-Sea Transfer (CBLAST) DRI (http://www.whoi.edu/science/AOPE/dept/CBLASTmain.html). Our study is performed in close collaboration with Dr. Lian Shen at Johns Hopkins University and other modelers and experimentalists.

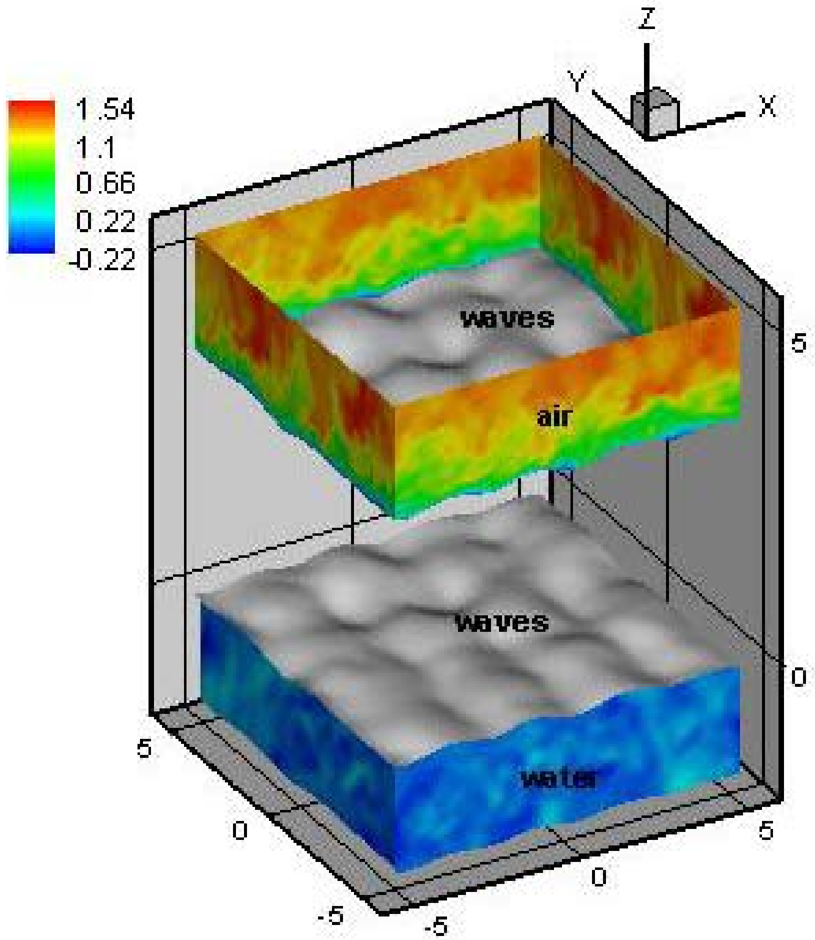

Figure 1. Interaction among winds, swells, and underwater currents. Plotted are surface wave profile and contours of air and water streamwise (defined as the direction of wave propagation) velocity normalized by the phase velocity of the dominant wave.

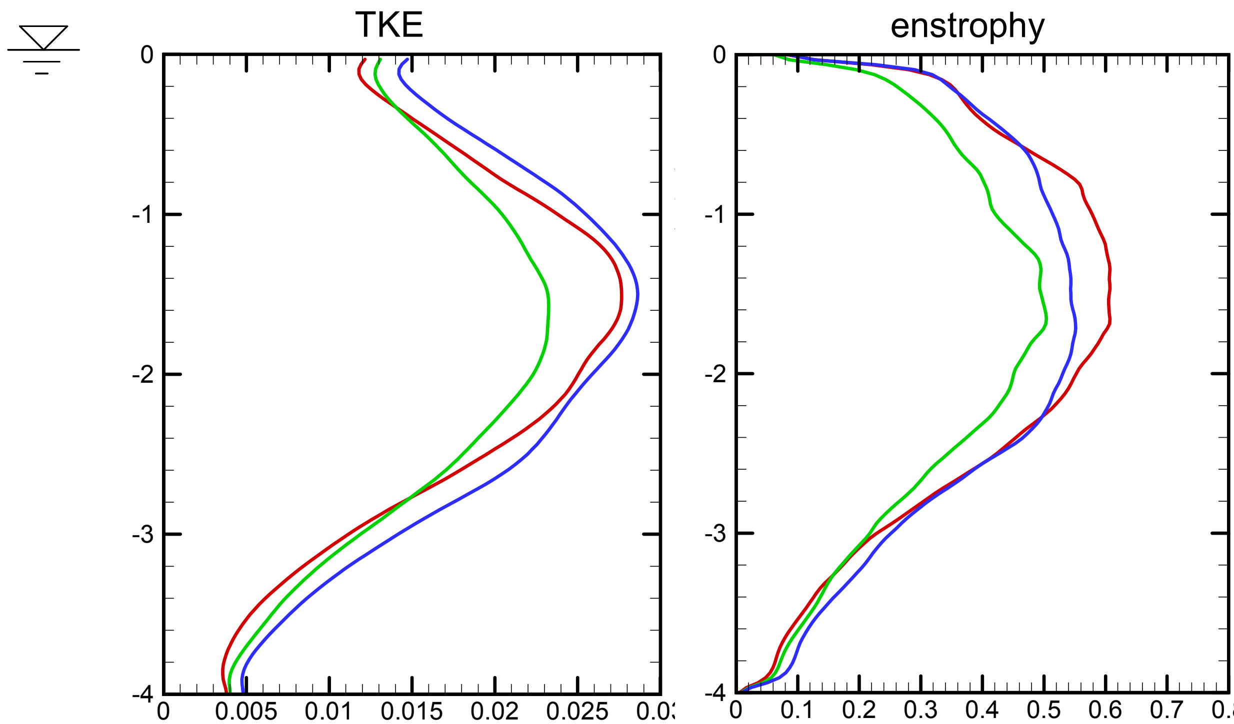

Figure 2. Effects of wave-current interaction on ocean turbulence. Plotted are vertical profiles of turbulent kinetic energy and enstrophy near water surface. Red line: wave against current, slope of dominant wave $ka = 0.05$***; green line: wave along current, slope of dominant wave*** $ka = 0.05$***; blue line: wave against current, slope of dominant wave*** $ka = 0.1$***;***

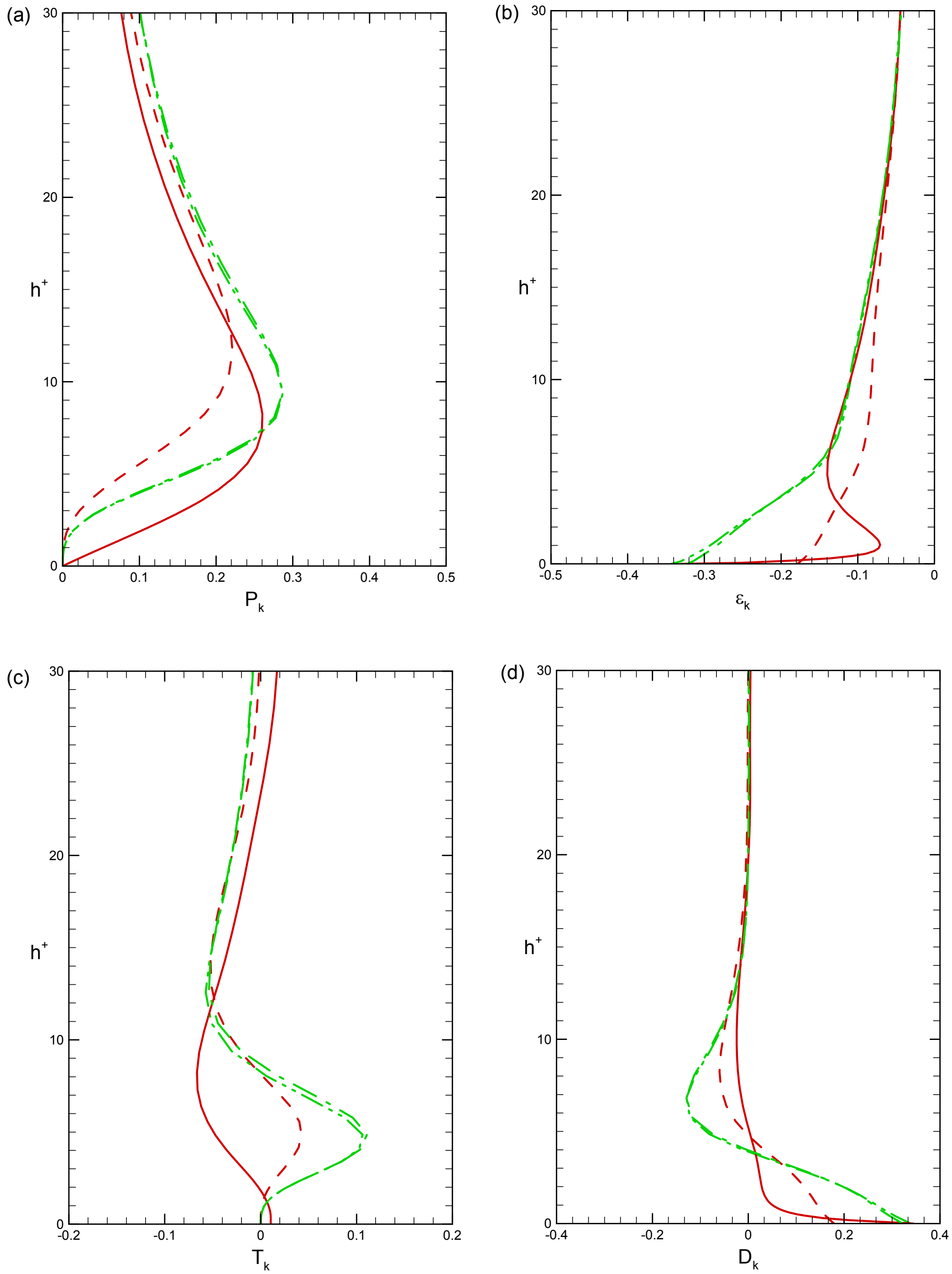

Figure 3. Variations of turbulent kinetic energy budget terms near the air-sea interface (solid line: water side; dash-dot line: air side) and solid walls (dashed line: water; dash-dot-dot line; air) for:
(a) turbulence production terms; (b) dissipation terms; (c) transport due to turbulence velocity fluctuations; and (d) viscous diffusion term.

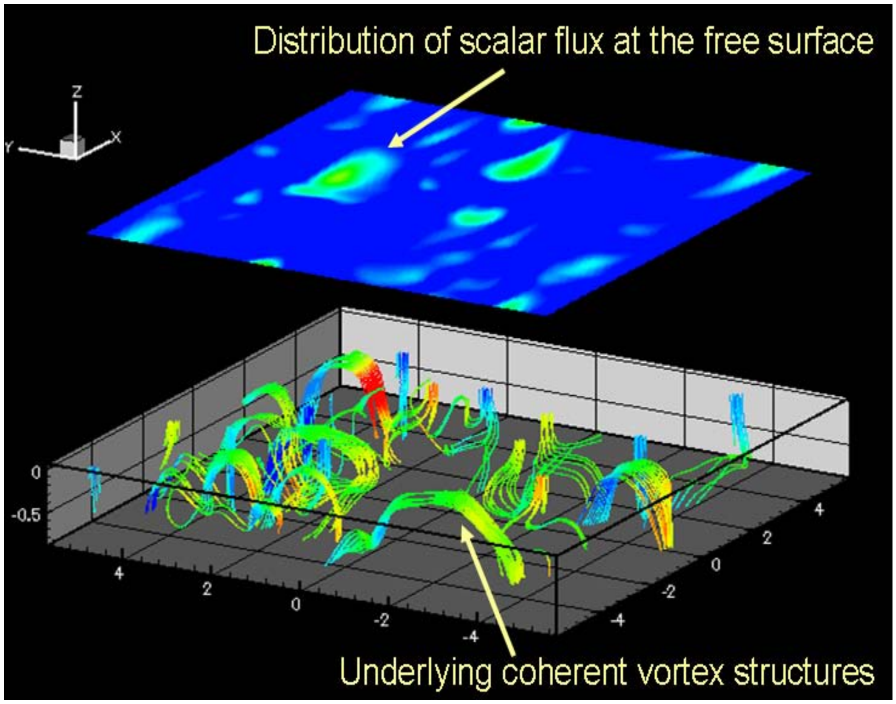

Figure 4. Dependence of surface flux of a passive scalar on coherent vortical structures in the ocean. Distribution of scalar flux at the water surface is represented by color contours with light color corresponding to high flux rate. Coherent vortex structures in the underlying bulk flow are indicated by vortex lines.