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

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Award Number: N000140110159

LONG-TERM GOAL

The main goal is to understand the detailed mechanisms of air-sea coupling at small spatial scales by performing LES of both air and ocean turbulent flows with coupled free-surface boundary conditions. The primary focus and an ultimate object 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 specific objectives are:

- Development of DNS/LES capabilities for the coupled air-ocean-wave flow field including the turbulent flows in both air and water
- Development, calibration and validation of specialized physics-based subgrid-scale (SGS) models for the atmosphere-ocean WBL
- Direct quantitative comparison and cross-validation of LES simulations with experimental/field measurements
- Elucidation of the structures and dynamics for turbulent flows in the vicinity of the air-sea interface
- Assessment of the physical mechanisms of the key WBL transport processes
- Parameterizations of the momentum, mass and heat transfer in the WBL for coupled air-ocean-wave boundary modeling

APPROACH

To understand the coupling dynamics within the air-ocean-wave system, both the air and ocean turbulent flows need to be resolved with coupled free-surface boundary conditions. To accomplish this, we develop two novel and complementary computational approaches: (a) for low wind speed (<5 m/s), a boundary interface tracking method (BITM) which utilizes boundary-fitted meshes; and, (b) for

Report Documentation Page	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE **30 SEP 2001**	2. REPORT TYPE	3. DATES COVERED **00-00-2001 to 00-00-2001**

4. TITLE AND SUBTITLE **Mechanistic Investigation of Small-Scale Air-Sea Coupled Dynamics Using LES**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Ocean Engineering,,Massachusetts Institute of Technology,,Cambridge,,MA, 02139**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The main goal is to understand the detailed mechanisms of air-sea coupling at small spatial scales by performing LES of both air and ocean turbulent flows with coupled free-surface boundary conditions. The primary focus and an ultimate object 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).

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a REPORT **unclassified**	b ABSTRACT **unclassified**	c THIS PAGE **unclassified**	**Same as Report (SAR)**	**7**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

moderate wind speed (>5 m/s), where the waves steepen/break, an Eulerian interface capturing method (EICM) based on a level set approach.

In BITM, the incompressible Navier-Stokes equations for both the air and water based on primitive-variable formulation are solved. The transport of scalars is also implemented in the BITM. Initially, we limit our scope to passive scalars. However, non-passive effects such as buoyancy associated with temperature and salinity variations can be readily incorporated later as necessary. At the air-water interface, 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 finite-difference schemes in the vertical direction. Explicit Runge-Kutta schemes are used for the time integration of the flow field as well as 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 air-water interface is represented by the zeroth level set of the scalar, and the sign of the scalar determines fluid properties. 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. The governing equations are discretized on an Eulerian grid, which is staggered in a MAC-type format where velocities are offset on the grid from the pressure and level set function.

WORK COMPLETED

Over the first year of this five-year project, substantial progress has been made towards numerical capabilities development and initial investigation on the hydrodynamics and transport process within the atmosphere-ocean wave boundary layer. The major work completed includes:

- Investigation on the scalar transport process in turbulent flows near the air-sea interface. The dependence of scalar transport on turbulent coherent structures is quantified using a novel conditionally-averaging technique.

- Development of DNS/LES capability for coupled air-water flows. The LES for complex geometries, such as the interaction of turbulent flows with steep surface waves, has been investigated systematically. Of significant importance, the commutation error associated with wave geometry were quantified and investigated for the first time.

- Spilling breaking wave simulation: The level set method has been used to simulate a spilling breaking events for a range of initial wave amplitudes. Dissipation of the events is being quantified for model development.

- Drop impact simulation: The level set method has been used to simulate, in two-dimensions and for axisymetric flows, the impact of a water droplet on a quiescent surface. This quantifies the robustness of the level set method for performing surface breakup and reformation as well as air-entrainment.

RESULTS

We perform numerical simulation for the turbulent transport of passive scalars near the air-water interface. From an ensemble of simulation results, the structure of free-surface boundary layers for the velocity and scalar are elucidated. With a novel conditionally-averaging technique, the dependence of scalar transport on turbulent coherent structures is quantified for the first time. It is found that hairpin vortical structures play a significant role in the transport of scalars towards the free surface (Figure 1), while surface-connecting vortices convect the scalars away from the surface (Figure 2). These processes together with splats and anti-splats provide the underlying physics for the modeling of gas and heat transport across air-sea interfaces. The key results in this aspect of research are currently being incorporated into two papers to be submitted to *Journal of Fluid Mechanics* (References 3 & 4).

A systematic study is performed for the numerical simulation of turbulent flows interacting with large-amplitude surface waves. Our focus is on the large-eddy simulation in complex geometries such as steep waves. It is found that the commutation error on irregular grids, which is caused by the incompatibility between filtering operation and spatial derivatives, has the same magnitude as the true SGS stresses. The accurate quantification of commutation error in wave field is the first in its kind and provides a framework for the systematic development of turbulence modeling.

Simulations to test the robustness of the level set method for surface breakup, reformation and air-entrainment have been performed using a water droplet impact as the test problem. Tests have been performed for both two-dimensional and axisymetric cases. Figure 3 shows the splash profile and vortical structure in both the air and the water for a two-dimensional drop impact profile. While the air vorticies dominate the image, a pair of counter rotating vorticies exists in the water at the center beneath the impact point.

Significant progress has been made in the simulation of spilling breaking waves and the quantification of the dissipation surrounding such events. Figure 4 shows a spilling breaking wave profile just after the toe of the bulge has begun to slide down the face. Cuts along the crest at this time show dissipation profiles along the wave. The largest dissipation region occurs at the location of this eddy that is associated with the toe.

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, investigation on the transport process, and parameterization for the prediction of air-sea interaction.

TRANSITIONS

The extensive numerical datasets obtained from this project will be used for the cross-calibration with measurements in the latter years of this project when measurement data are obtained. The numerical results will also be used to provide information on physical quantities difficult to measure and to verify experimental databases. The numerical capabilities developed in this project will also provide a framework for the parameterization of coupled air-ocean-wave dynamics.

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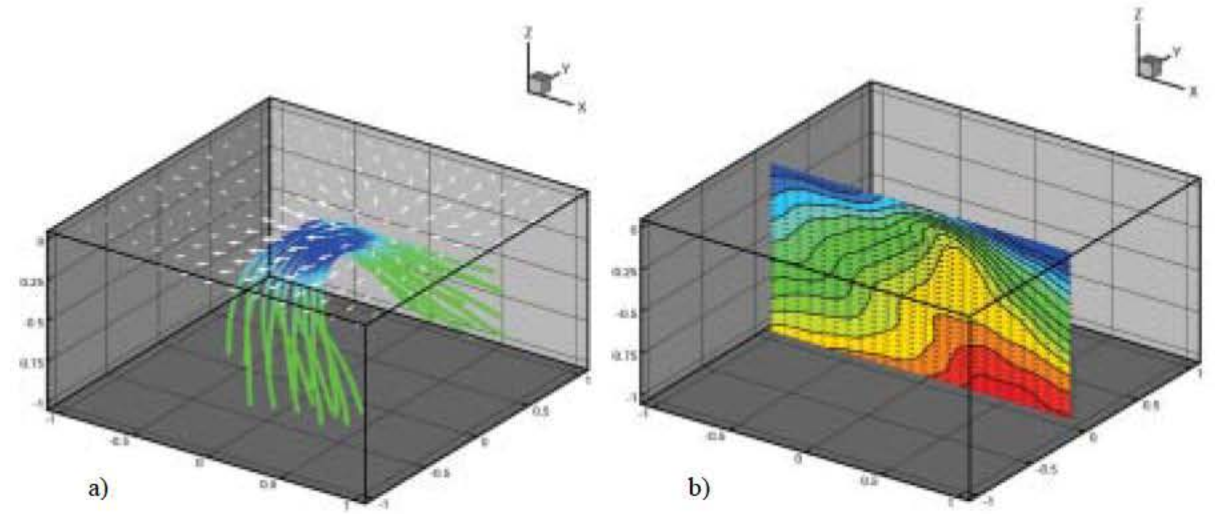

Figure 1. Enhancement of upward scalar transport due to coherent hairpin vortices. (a) Vortex lines in a hairpin vortex structure. The velocity vectors show the splats motion on the air-water interface. (b) Scalar contours on the vertical center plane of the vortex structure.

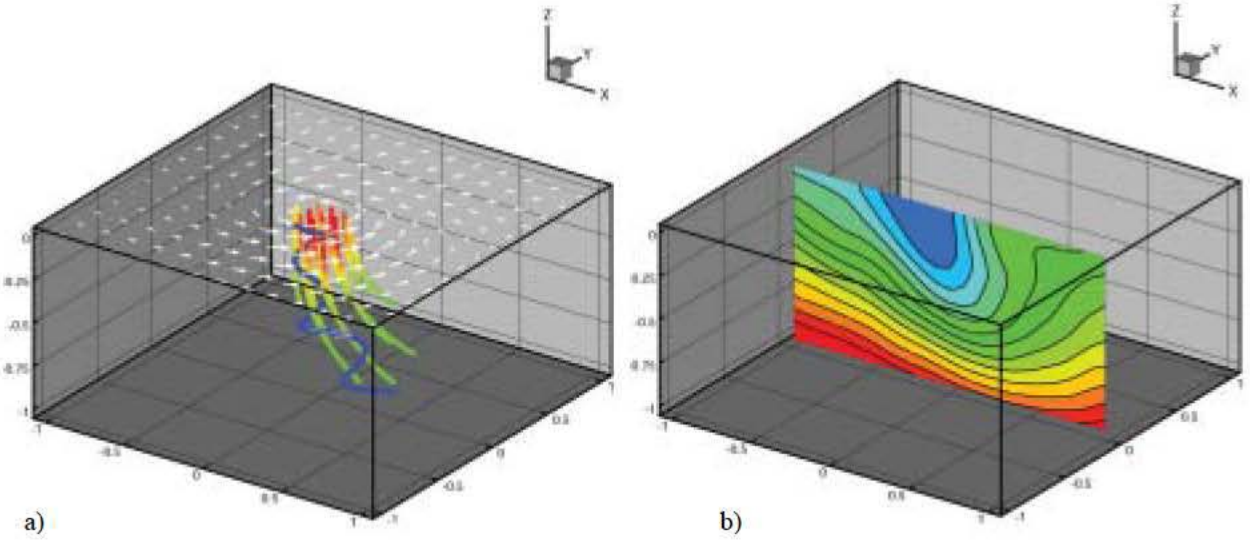

Figure 2. Enhancement of downward scalar transport due to surface-connected vortices. (a) Vortex lines in a surface-connected vortex structure. The blue streamline shows the downward spiral motion. (b) Scalar contours on the vertical center plane of the vortex structure.

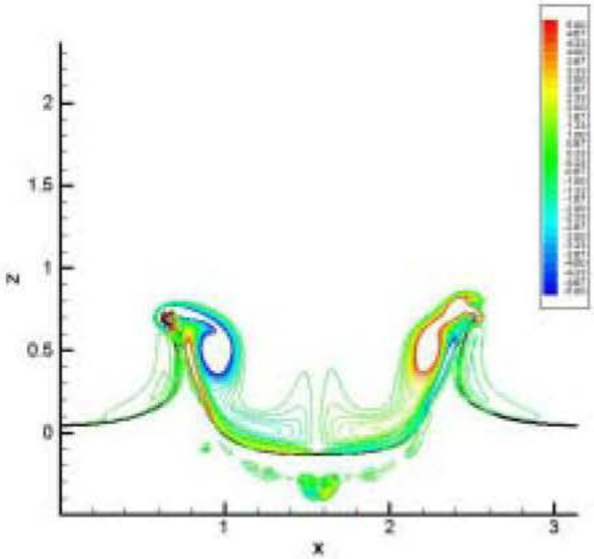

Figure 3. Resulting splash up of a two-dimensional drop impact on a quiescent surface. Black line is the air-water interface. Contours of vorticity are shown in both the air and water. $Re_w = 10^4$, $Fr_d = 4$. ***Note the small but significant strength vortices in the water beneath the impact point.***

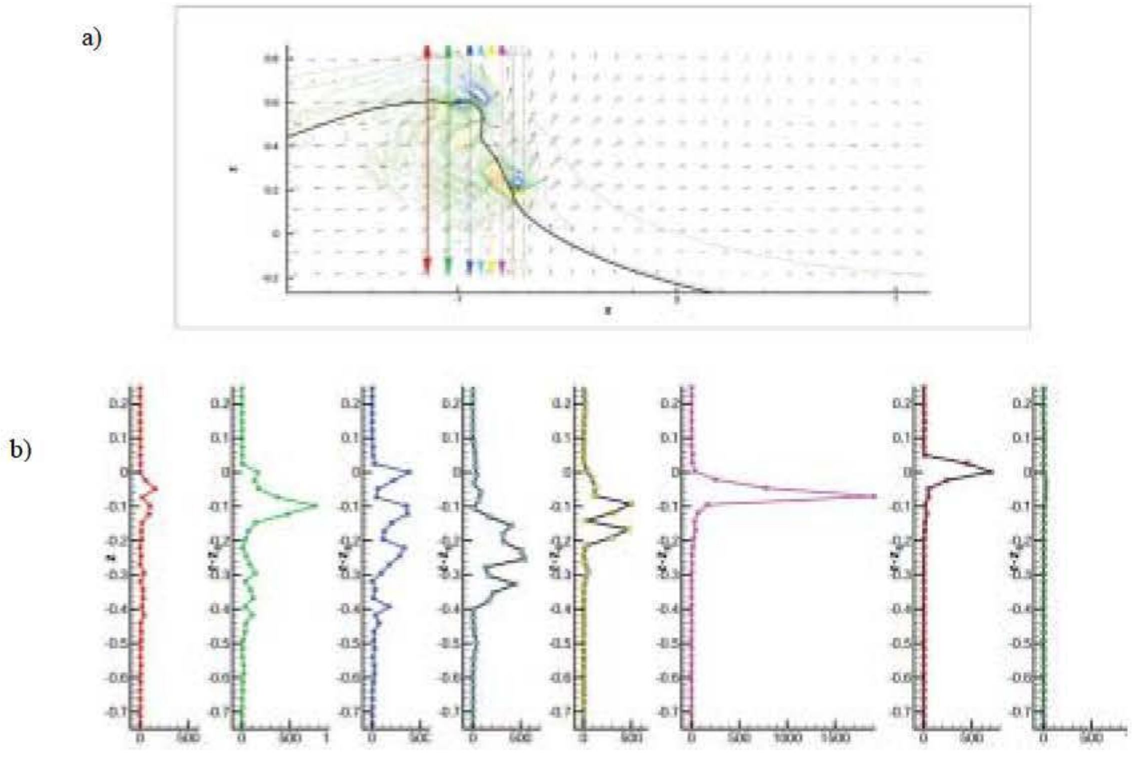

Figure 4. Vortical structure and dissipation profiles of a two-dimensional spilling breaking wave: $Re_w=2000$, $Fr=1$. ***(a) Contours of vorticity and every fourth velocity vector. Black line is air-water interface. Vertical colored arrows are slices where dissipation profiles are shown. (b) Total dissipation as a function of depth*** $(z-z_{fs})$ ***along crest of wave. Largest point of dissipation (purple cut) is location of strong eddy that is moving down the forward face of the wave.***