

Large Eddy Simulation of Ocean Boundary Layer Entrainment

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LONG-TERM GOALS

Traditional approaches to modeling the marine boundary layer have concentrated on processes occurring near the sea-air interface. While this is appropriate and has been successful to a large degree, it has not produced a model that is accurate to the degree required for many Navy applications. We believe that the study of the dynamics of the wave boundary layer must be expanded to include those at the top of the marine boundary layer. Our long-term goal is to understand the interaction between the entrainment process and the wave boundary layer.

OBJECTIVES

The specific objectives are to address the following issues.

- (1) What is the budget of turbulent kinetic energy of the marine convective boundary layer in the presence of partially stable surface layer under *low-wind* conditions? How well is the Monin-Obukhov similarity theory applied to the wave boundary layer?
- (2) What are the dominant coherent structures in the marine surface layer? What is their role in the production of turbulent kinetic energy? What is their relationship with the mixed-layer plumes that reach the lifting condensation level?
- (3) How does the entrainment process interact with the wave boundary layer? How does the small-scale variability at the wave boundary layer affect the entrainment process?
- (4) What is the effect of large-scale horizontal inhomogeneity on the small-scale structures and processes in the marine boundary layer?
- (5) What are the causes of instability at the top of the boundary layer? Under what conditions do warmer, wetter, layers form above the top of the boundary layer.

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE 30 SEP 2001		2. REPORT TYPE		3. DATES COVERED 00-00-2001 to 00-00-2001	
4. TITLE AND SUBTITLE Large Eddy Simulation of Ocean Boundary Layer Entrainment				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 Mechanical Engineering,,The University of Iowa,,Iowa City,,IA, 52242				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					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 7	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

APPROACH

Large-eddy simulation technique (LES) is used to investigate the above issues. A finite-volume-based LES code solves the filtered incompressible Navier-Stokes equations with Boussinesq approximation on a generalized body-fitted coordinate system. A dynamic subgrid-scale model is employed to represent unresolved turbulent motions. The code was originally developed by Zang et al. (1994) at Stanford Environmental Fluid Mechanics Laboratory, and have been greatly enhanced by the PIs as described below.

To simulate the marine boundary layer and study the interaction between the entrainment process and the wave boundary layer, we aim to first reproduce the LES of small scale processes and entrainment in a stratocumulus marine boundary layer by Stevens et al. (2000). To achieve this goal, the transport equation for the total water mixing ratio and the parameterization of longwave radiation flux $F_r(z)$ have to be added to the LES code.

$$F_r(z) = F_r(H) \exp\left(-K_a \int_z^H \rho_o q_c dz\right)$$

where H is the height of the domain and q_c is cloud water (precipitation is neglected).

Motivated by some works presented at the 2001 ONR CBLAST workshop, such as free surface disruptions and sea spray, we decided to develop and implement an advanced two-phase model on the LES code (not proposed in the original proposal) in hope to simulate and capture realistic sea-air interfacial phenomena. To achieve this goal, we need to

- (1) replace the reduced pressure in the code by the total pressure,
- (2) use a higher-order interpolation scheme and a non-oscillatory upwind scheme,
- (3) implement a more accurate fraction step method,
- (4) add the level set function ϕ and the level set equation to track the interface,
- (5) develop a re-initialization scheme for the level set function.

The level set method (Sethian 2000) allows simulation of two-phase binary fluid flows with sharp interfaces, such as wave breaking (Iafrafi et al. 2001).

The ultimate goal is to integrate the level set method into the simulation of marine boundary layer, allowing true interaction of entrainment processes and wave boundary layer. The integration is very challenging due to the presence of multiscale structures. Three options are possible. One option is to have a single grid which clusters grid points near the wave boundary layer and the capping inversion layer. The second option is to use a composite two-grid system in a single simulation: one grid covering the whole marine boundary layer, the other grid covering the relatively thin wave boundary layer only. The third option is to conduct two separate simulations. An auxiliary simulation of the marine boundary layer is to generate the upper boundary condition for the wave boundary layer. The main simulation is to simulate the wave boundary layer. The first two options permit two-way interaction. The third option is one-way interaction by assuming that the characteristic time scales of

the two layers are quite distinct. The access to supercomputers is essential to the success of the integrated simulations.

WORK COMPLETED

- (1) Jan. 2001: attended the CBLAST workshop.
- (2) Nov. 00 - Feb. 01: recruited a graduate student to work on the project.
- (3) Feb. 01 - May 01: familiarized the student with LES.
- (4) May 01 - Sep. 01: modified the LES code by adding
 - the transport equation for the water mixing ratio and
 - the longwave radiation flux model to simulate the entrainment process of the marine boundary layer. The students also learned about grid generation during this period.
- (5) Jan. - Sep. 01: developing the level set method to be used later for simulation of atmosphere-ocean interaction. The LES code has been greatly improved by
 - replacing the reduced pressure by the total pressure (namely including the hydrostatic pressure in the z-momentum equation),
 - using an improved interpolation scheme on nonuniform mesh to calculate pressure at faces of control volumes (this is necessary to ensure the numerical stability due to an increase in the magnitude of pressure),
 - implementing the fraction step method of Choi and Moin (1994) (we had tested four variants of the fraction step method and found that the above method gave the best results in terms of accuracy and stability),
 - implementing the level set equation and the re-initialization scheme to track the interface of a two-phase flow.
- (6) Jan. - Sep. 01: reviewed literatures and proceedings and operation summary of CEPEX (Central Equatorial Pacific Experiment).

For the simulation of the entrainment process in the marine boundary layer, we are about to simulate a case with a coarse grid of $64 \times 64 \times 48$ covering a domain of $3.2 \times 3.2 \times 1.2 \text{ km}^3$. As for the level set method, we have been testing the code by simulating a two-dimensional two-phase flow (air-water) past a submerged hydrofoil.

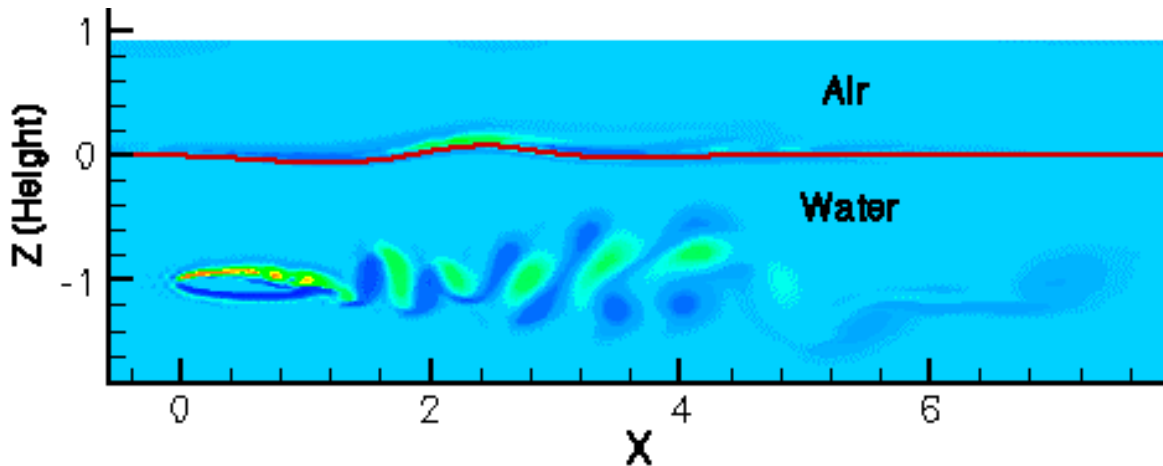
The original tasks proposed in the proposal for the fiscal year 2001 are listed below for comparison.

- (1) Familiarize the student with two large-eddy simulation codes.
- (2) Contact other experimenters and collect data from existing experimental data sets.
- (3) Examine thoroughly the data collected during the Combined Sensor Program and determine large-scale forcing conditions.
- (4) Carry out baseline calculations with uniform grid.
- (5) Analyze preliminary solutions.

We have completed tasks 1, 2, and 3 (Lin contacted a CBLAST experimenter about the remote sensing data; Lin and Eichinger also discussed about lidar measurement of vertical velocity profiles over lakes to get an idea about the physical boundary conditions for LES). We are in the process of completing tasks 4 and 5. At this stage, all the test simulations were performed on local HP workstations and SGI PCA machine using very coarse grids or 2D cases for the code development. Since it is expected to enter production runs in the next fiscal year, we will soon apply for computational time on the NAVOCEANO computers at the John C. Stennis Space Center.

RESULTS

At the time of preparing the report, we are still verifying and validating the codes. Currently we have two versions of the LES code. One version is to simulate the marine boundary layer without the level set method. The other version is to simulate the free surface flow without the transport equation for water mixing ratio and the longwave radiation flux model. For instance, figure 1 shows the contours of vorticity from the simulation of a two-dimensional free surface flow perturbed by a submerged hydrofoil at Reynolds number 1,000. The free surface is located at about $z = 0$.



*Figure 1. Two-dimensional free surface flow
[The vorticity contours of the unsteady flow with a free surface
denoted by the red line]*

IMPACT/APPLICATIONS

The level set method has been used to track the evolving interfaces in the problems of fluid mechanics, materials science and other sciences, such as rise of air bubble in water (Sussman et al., 1999) and evolution of two-dimensional breaking wave (Iafrati et al., 2001). To my knowledge, it has never been applied to the problem of the wave boundary layer. The level set method has a potential to simulate realistic free surface wave and allows investigation of its coupling with the structures above the wave boundary layer and those at the top of the marine boundary layer.

TRANSITIONS

NA

RELATED PROJECTS

Lin is also developing a four-dimensional variational data assimilation technique which can fuse lidar radial velocity data into a LES-like model to recover complete wind and temperature data (http://css.engineering.uiowa.edu/~ching/resh_adj.html). If someone can provide with radial velocity data at the field experiment site, it is possible to use this technique to provide initial and boundary conditions for the above simulations.

Since one of the goals of the CBLAST DRI is to investigate free surface disruptions and bubbly flows which are essentially two-phase flows involving large interface deformations. We'd like to bring to the attention of the group the diffuse-interface methods (Anderson and McFadden, 1998) and the lattice-Boltzmann methods (Chen and Doolen, 1998). These methods have potentials to simulate complicated interfacial phenomena. A brief description of the research related to lattice Boltzmann methods conducted by Lin is online at http://css.engineering.uiowa.edu/~ching/resh_lbm.html.

SUMMARY

The project provides an opportunity to learn about the characteristics of the marine boundary layer and the wave boundary layer. It also stimulates us to apply the level set method to the challenging problem. We hope that in the end the improved numerical scheme can generate physically meaningful data to shed light on the aforementioned issues. The LES code with improved capabilities could also be applied to simulate and study other hydrodynamics problems with free surface.

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