Subgrid Scale Modeling For LES Simulation of Flow In A Turbulent Bottom Boundary Layer

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Award #: N00014-00-1-0218
http://www.oe.fau.edu

LONG-TERM GOAL

The long-term goal of this work is to develop an accurate and efficient LES (large-eddy simulation) model of turbulent flows in oceanic boundary layers.

OBJECTIVES

The major objectives to be achieved are:

(1) Acquire better understanding of specific properties of oceanic boundary layers, particular attention being paid to statistics of small-scale coherent structures and their adequate representation by subgrid-scale (SGS) models.

(2) Implement the Smagorinsky and dynamic SGS models and validate them for oceanic boundary layers through comparison with direct numerical simulations (DNS) and autonomous underwater vehicle (AUV) field data.

(3) Develop and test a SGS model capable of accurate parameterization of the effects of small-scale coherent structures.

APPROACH

The work involves theoretical analysis, numerical computations, and comparison with field measurements. The primary research tools are three-dimensional DNS and LES models, which allow simulation of turbulent layers in shallow water.

WORK COMPLETED

The three-dimensional numerical model developed by Slinn & Riley (1998) has been modified to describe turbulent penetrative convection in shallow water caused by the passage of a cold air front. This flow was chosen because of an extensive database of field measurements collected during AUV experiments in December 1998. We started with two high resolution Direct Numerical Simulations performed at Rayleigh number $Ra=7\times10^{8}$ with different background density stratification (Richardson number $Ri = 2$ and 10). Further, we have implemented the standard LES Smagorinsky model and the scaling version of the dynamic LES SGS model proposed for turbulent convection by Wong & Lilly (1994). The models have been tested and validated through comparison with results of DNS. In the

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2000**	2. REPORT TYPE	3. DATES COVERED **00-00-2000 to 00-00-2000**
4. TITLE AND SUBTITLE **Subgrid Scale Modeling For LES Simulation of Flow In A Turbulent Bottom Boundary Layer**		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,Florida Atlantic University,,,777 Glades Road,,Boca Raton,,Fl,33431**		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

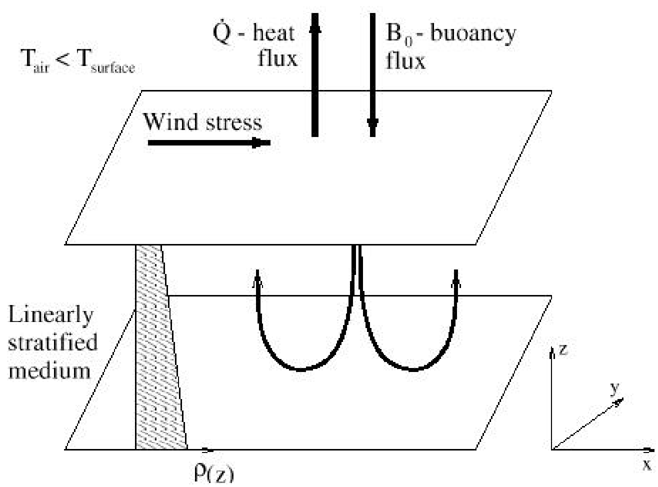
15. SUBJECT TERMS

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**	

course of the work, we have found that the high Rayleigh numbers observed in typical oceanic flows can be achieved only upon further modification of the model, in particular, use of approximate boundary conditions at the upper surface becomes expedient.

RESULTS

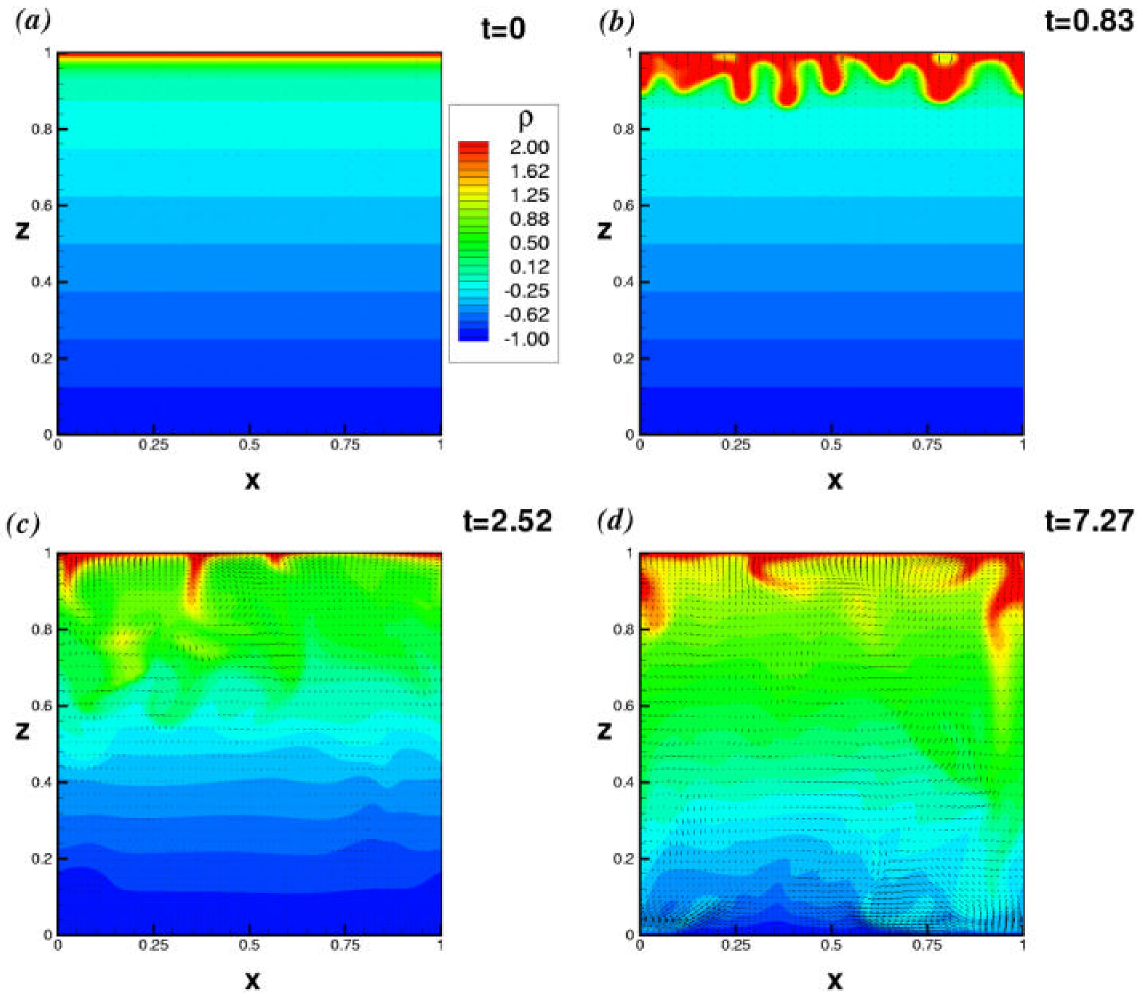
We consider the flow in a horizontal layer confined between a smooth no-slip bottom and rigid free-slip surface at the top (see Figure 1). The flow is assumed homogeneous in both horizontal directions so that periodic boundary conditions can be applied. The flow is generated by the mechanism of thermal convection, which arises due to heat exchange (cooling) at the upper surface. Stable background stratification is present initially, caused by a background temperature gradient.



1. Schematics of the model problem.

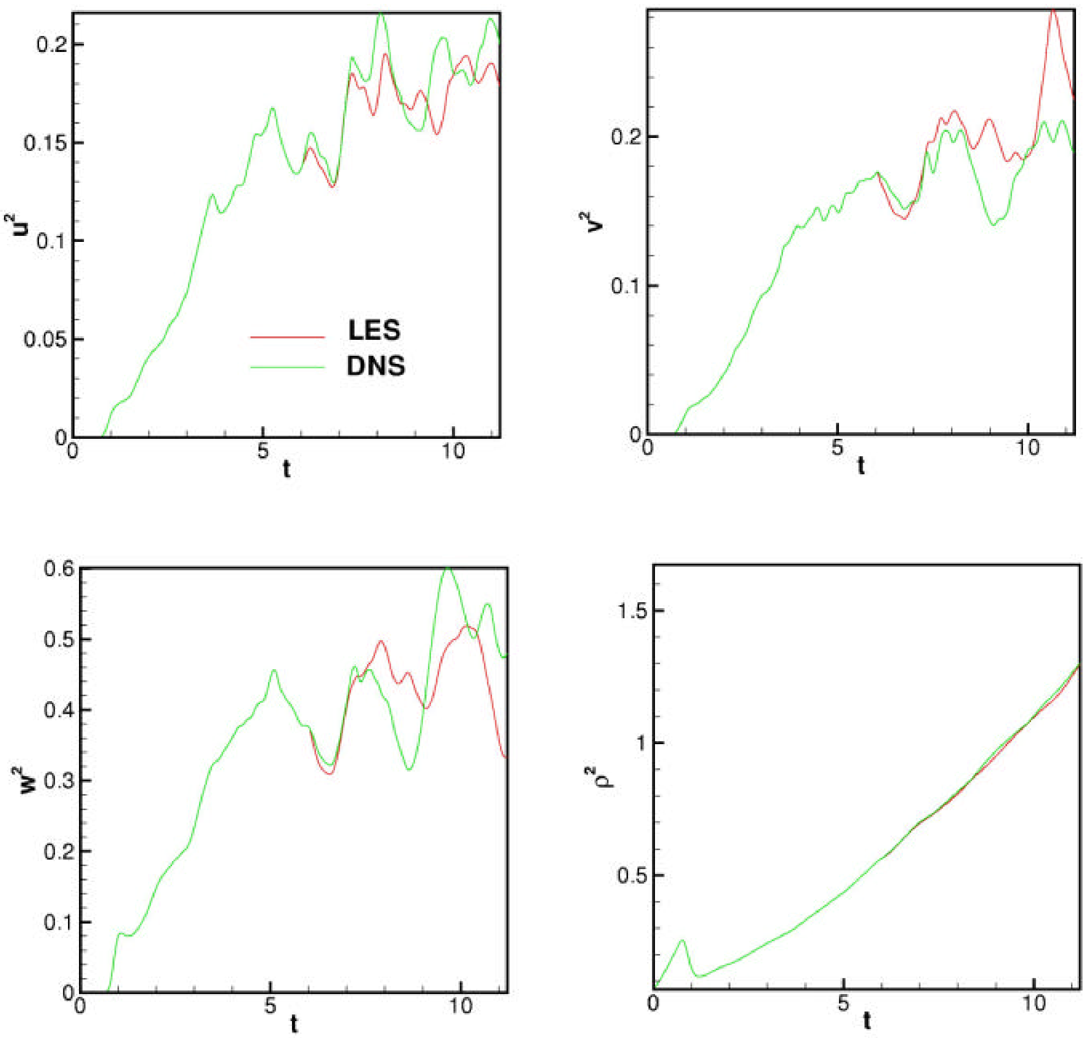
The flow evolution is illustrated in Figure 2. Instantaneous density and velocity fields calculated in the DNS run with the stronger background stratification are shown in a vertical cross-section from the three-dimensional simulation. It can be seen how the initial diffusive layer (Figure 2a) becomes unstable (Figure 2b) and creates turbulent convective motion (Figure 2c). The turbulence penetrates the layer and, after some time, reaches the bottom boundary, forming a turbulent layer across the water column (Figure 2d).

Our calculations have confirmed the conclusion made previously for Rayleigh-Benard convection (see, *e.g.,* Edison, 1985) that the accuracy of simulations depends crucially on the numerical resolution of the diffusive boundary layer at the upper surface. In the DNS runs, the vertical grid size was decreased almost tenfold in this region. In LES computations, the vertical grid size can be increased in comparison to DNS only upon replacing the boundary condition of a given heat flux at the surface by its approximation over the grid control volume closest to the boundary. In the first LES simulations presented in this report, we retain the exact boundary condition and apply the SGS model in the horizontal directions.



2. Evolution of the density field in a two-dimensional cross-section from the three-dimensional DNS experiments at different times.

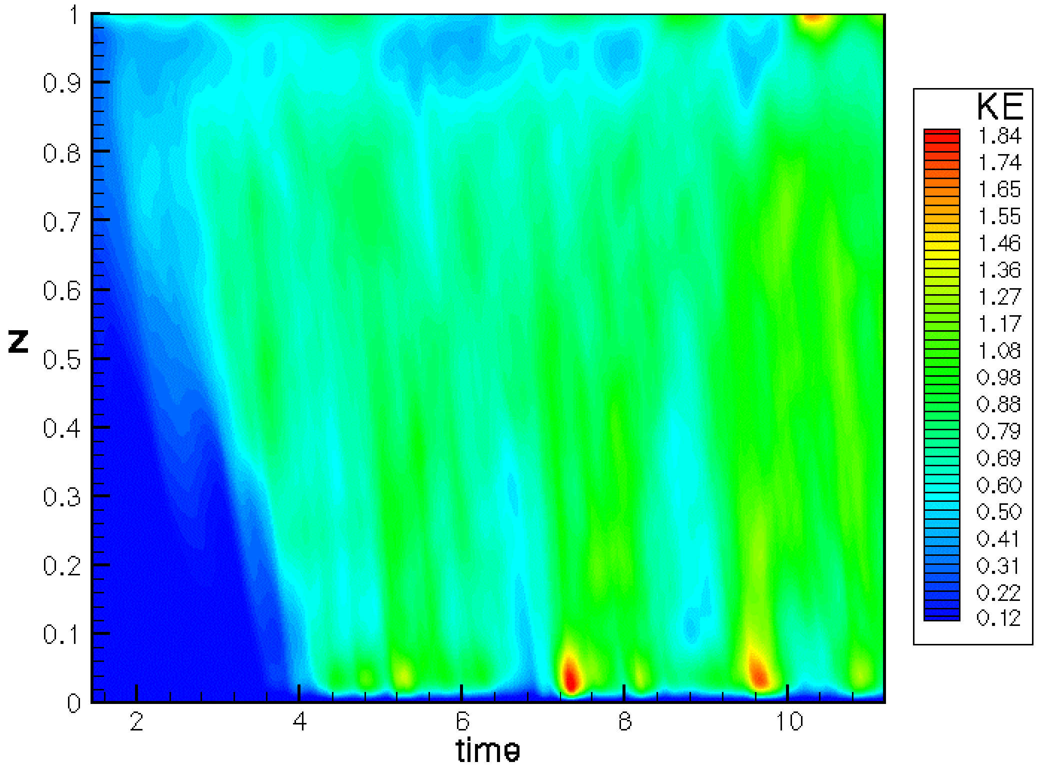
Two SGS models have been implemented in the code. One, the so-called scaling formulation of the dynamic (Germano) model proposed for turbulent convection by Wong & Lilly (1994), has been found to produce relatively weak SGS stresses. By comparison, the classical Smagorinsky model with fixed turbulent Prandtl number, $Pr_\tau=1/2$, has proven robust and capable of predicting the average flow characteristics in close agreement with DNS. Comparison between LES and DNS is illustrated in Figure 3. Figure 4 shows the time evolution of the horizontally averaged turbulent kinetic energy as a function of height from the boundaries.



3. Comparison of TKE and potential energy contributions between LES and DNS simulations.

IMPACT/APPLICATIONS

An important potential benefit of our work for society is that it serves to develop and validate an accurate and efficient LES model for turbulent flows in shallow water. The model, including effects of small-scale coherent structures on SGS stresses, will enhance our ability to simulate such important processes as diapycnal mixing in shallow water, wave boundary layers, or beach processes. Furthermore, our work contributes to better understanding of properties of turbulent flows in the shallow ocean, in particular, turbulent penetrative convection caused by surface cooling.



4. TKE distribution, averaged in x-y plane from a DNS computation.

TRANSITIONS

One important transition in our work has been caused by the fact that we extensively used the field observations from the adverse weather experiments conducted in a related project to validate the numerical models. Accordingly, the simulations have focused on turbulent convection generated by surface cooling rather than bottom boundary layers with prescribed free-stream conditions as was initially planned for the project.

RELATED PROJECTS

The work is carried out in conjunction with field measurements under grant N00014-96-1-5023.

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PUBLICATIONS

In preparation.