

Turbulence Modeling in Stratified Flows Subject to Advective Buoyancy Fluxes

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Award #: N00014-03-1-0422

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LONG-TERM GOALS

We are performing, in collaboration with Professor Mark Stacey of UC Berkeley, simulations of the mixing processes in stratified free-surface flows, which are typically found in the near-coastal domain. The goal of the proposed work is to determine which turbulence model will most efficiently and accurately predict the state of flow in estuaries and the coastal ocean, including both the current structure and the mixing coefficients. In particular, we are trying to determine whether turbulence closure parameterizations should be modified in the presence of sheared horizontal advection of a background horizontal density gradient.

OBJECTIVES

The primary question to be addressed is: How can we most accurately and most efficiently model turbulent mixing in estuaries and coastal circulation models where both vertical and horizontal density gradients are relevant. In particular, we are trying to determine whether turbulence closure parameterizations should be modified in the presence of sheared horizontal advection of a background horizontal density gradient. Other questions to be addressed include: How do shear, stratification, and turbulence interact in the presence of a longitudinal density gradient? What turbulence models perform best in the presence of a horizontal buoyancy flux? In a system with reversing advective buoyancy flux can models predict mixing and transport over long timescales?

APPROACH

In order to answer these questions, our joint approach (with Stacey at Berkeley) will involve a combination of Large Eddy Simulation (LES) and Reynolds-Averaged-Navier-Stokes (RANS) modeling. The large eddy simulation will allow us to examine the structure and dynamics of turbulence in our flow environment, and will produce data sets for use with the RANS modeling. The RANS model will be used to examine a variety of turbulence closures, and evaluate their performance against field data collected by Stacey and his group and the LES-produced data.

WORK COMPLETED

The project just got underway in March 2003. To date we have developed modifications for the constants in the k - ϵ turbulence model. In particular, we have developed parameterizations for the coefficients c_μ , Pr_t , c_{ϵ_2} , and c_{ϵ_3} as a function of the turbulent Froude number and the turbulent Reynolds number, using the database developed in a previous ONR-sponsored project (see Shih et al., 2000, 2003). These parameterizations have been coded up and included in the GOTM code (Burchard et al., 1999) where their performance is being compared against the standard k - ϵ model and other versions of k - ϵ developed specifically for stratified flows.

RESULTS

The tests of the model were performed using the 1-D water column model GOTM, which is based on a modular format that enables it to be easily embedded in 3-D ocean circulation models and also allows for refinements or extensions for the turbulence models. We incorporated our proposed model into the GOTM code. Since none of the built in stability functions in GOTM modify their parameters

based on depth, we had to adapt the code to modify the parameters in k- ϵ model discussed above to be depth varying based on the local turbulent Froude number.

The test case we use is a pressure gradient driven open channel flow in which the density is held fixed at both the lower solid boundary and the upper free surface. This allows the flow to develop to a fully developed steady state with a non-uniform density profile. The Reynolds number, Re_τ and the Richardson number, Ri_τ , (based on the shear velocity) were 682 and 31 respectively. Previous studies by Garg et al. (2000) have shown that LES have produced results that are in good agreement with DNS results for open channel flows. Hence, we use an LES run with identical conditions to those in our test case to assess the predictions of our proposed model and that of the standard k- ϵ model with constant stability functions. The flow was allowed to develop to a converged solution using the standard k- ϵ model after which the stratification was imposed. The velocity and density profiles at the initial state (i.e. after spin up; non-dimensional time $t^*u_\tau/h = 0$) are shown in Figure 1 for both the standard k- ϵ and the modified k- ϵ . Superimposed on these plots are the LES profiles.

The velocity and density profiles at a non-dimensional time of $t^*u_\tau/h = 4.1$ are shown in Figure 2. It is clear from this figure that the modified k- ϵ is doing a better job of capturing the density profile as well as the velocity profile. The velocity and density profiles at a non-dimensional time of $t^*u_\tau/h = 14.6$ are shown in Figure 3. It is clear from this figure that the modified k- ϵ is still doing a better job of capturing the density profile but that there seems to be an issue with both models in capturing the velocity profile. We are currently working on trying to resolve this issue.

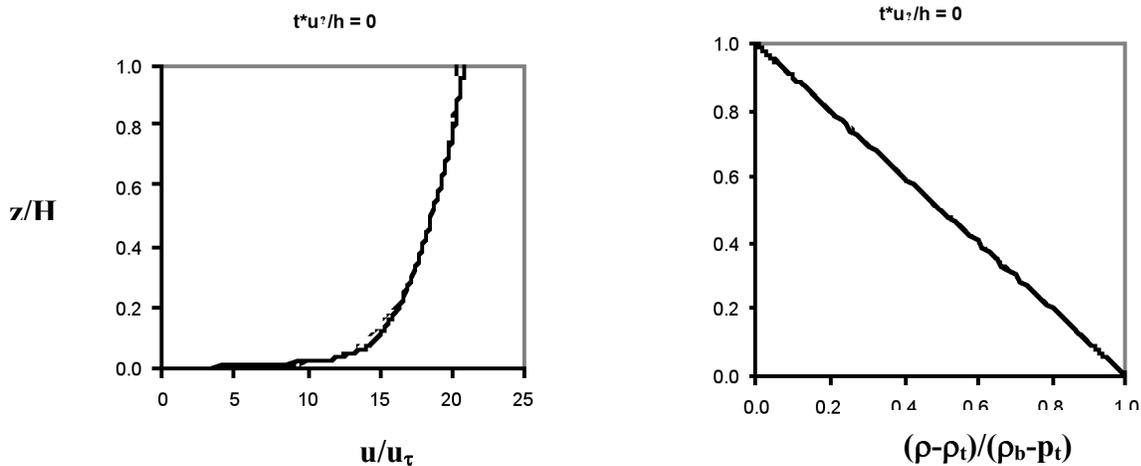


Figure 1: Plot of velocity and density profiles at $t^*u_\tau/h = 0$ for the LES (solid line); standard k- ϵ (dashed line); and modified k- ϵ (dotted line)

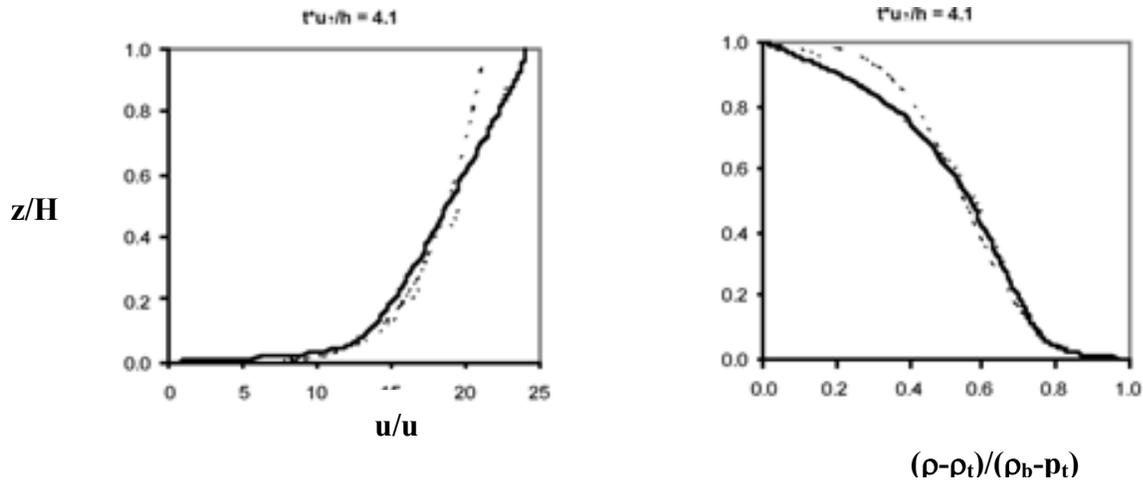


Figure 2: Plot of velocity and density profiles at $t u_\tau/h = 4.1$ for the LES (solid line); standard $k-\epsilon$ (dashed line); and modified $k-\epsilon$ (dotted line)

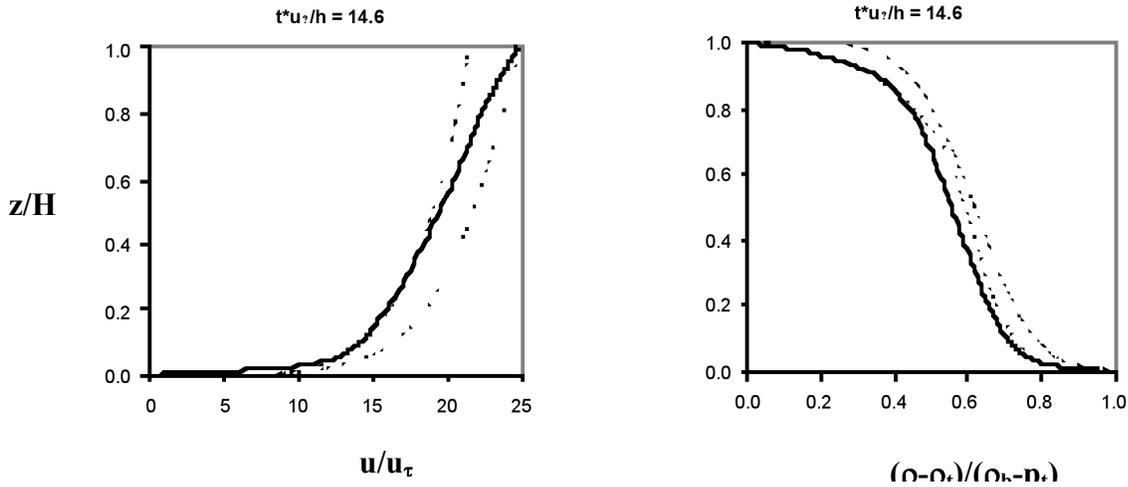


Figure 3: Plot of velocity and density profiles at $t u_\tau/h = 14.6$ for the LES (solid line); standard $k-\epsilon$ (dashed line); and modified $k-\epsilon$ (dotted line)

IMPACT/APPLICATIONS

The results demonstrate the intrinsic value of DNS and LES in that it allows us to calculate each term in a model or parameterization of the extant physics. Evaluation of existing turbulence closure models or commonly used sub-grid-scale parameterizations is therefore a lot more complete than with experiments alone.

TRANSITIONS

The numerical databases developed under separate ONR funding have been used in this project to develop new turbulence parameterizations for stratified flows, and to test these parameterizations. As part of our collaboration with Mark Stacey we are now discussing the development of an extensive field-measurement campaign (under separate funding) in South San Francisco Bay to develop an additional database to test the models developed during this project. This field campaign is motivated by the success to date of the approach we have adopted in this project. It will likely involve researchers from Stanford University, UC Berkeley, the USGS, and the University of Western Australia.

RELATED PROJECTS

Shear Production and Dissipation in a stratified tidal flow - ONR - (Monismith PI). Our fieldwork includes work on stratified tidal flows in which we are making Reynolds stress measurements using broadband ADCPs

An Experimental Study of a Breaking Interfacial Wave - NSF- (Koseff PI). In the laboratory we are performing experiments in an attempt to measure the mixing associated with a breaking internal wave at a stratified (two-layer) interface using the wave-generation technique of Rapp and Melville. In this work we are measuring the mixing efficiency associated with such an event.

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Shih, L.H., Koseff, J.R., Ivey, G.N., and J.H. Ferziger, 2003. "Prediction of fluxes from a homogeneous sheared stratified turbulence database", *Journal of Fluid Mechanics*, submitted.

PUBLICATIONS

Ferziger, J. H., Koseff, J.R., Shih, L.H., and S.K. Venayagamoorthy, 2003. “RANS models for stratified turbulence based on DNS data”, *Physics of Fluids*, in revision.

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