A Study of the Structure of the Near-Coastal Zone Water Column Using Numerical Simulations

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LONG-TERM GOALS

Our long-term goal is to understand how flows in near-coastal zone (20m to 100m) respond to a variety of forcing mechanisms including tidal pressure gradients, surface waves, surface heating and cooling, surface wave-bottom current interaction, and tidally generated bottom boundary currents. Because the nature of this response varies throughout the water column and depends strongly on the non-linear coupling of stratification, turbulence and flow structure characterizing the structure of the water column in this environment is a very difficult field measurement task.

OBJECTIVES

It is possible to gain some insight into the physics, and into our ability to model or parameterize the physics, by looking at a more idealized version of this problem using large eddy numerical simulations (LES). We are performing simulations of the mixing processes in the upper layer of the near-coastal, and deeper, using a periodic channel as the computational domain. Benefits of using numerical simulations, as compared to laboratory or field experiments, is the relative ease with which information about the turbulence can be extracted from the flow and the control over the external variables. The study has two fundamental goals: (1) Developing deeper understanding of the interaction between various physical mechanisms that affect the dynamics of the upper mixed layer in the near-coastal ocean and the deep ocean; and (2) Developing improved parameterizations of these processes for use in large eddy simulations (LES) and Reynolds-Averaged Navier-Stokes (RANS) models to be used in modeling on the larger scales.

APPROACH

The LES technique is employed to solve the Navier-Stokes equations for stratified turbulent channel flow numerically. A vortex forcing term has been added to simulate Langmuir circulations. The code employs the dynamic eddy viscosity model of Germano *et al.* (1991) with Lilly's (1992) least squares modification. This code, which was originally developed and implemented on the 400-node Intel Paragon XP/S supercomputer at SDSC by Garg *et al.* (1994), has been modified both to be portable to extant parallel computing platforms and to account for the additional physical phenomena we wish to examine. The code was run with a 128x256x128 grid on our local 40-node Compaq/Alpha Beowulf cluster (http://fluid.stanford.edu/baywulf /baywulf.html), and we also ran the code with similar resolution on the 260-node IBM Netfinity Linux Supercluster at the Maui High Performance Computing Center (http://www.mhpcc.edu/doc/huinalu.html).

WORK COMPLETED

Following Zhou (1999), we added the Craik-Leibovich vortex forcing term to the momentum equations in order to simulate Langmuir circulations. We also added the ability to vary the thickness of a thermocline density profile in the channel. Due to increases in computing power, higher Reynolds number ($Re_\tau = 480$ and 720) cases have also been completed to complement the $Re_\tau = 360$ cases. We also modified the code to allow us to run either Poiseulle flow cases, Couette flow cases, and mixed Poiseulle-Couette flows with and without Langmuir forcing. These modifications to the code allow us to examine the interactions among Langmuir circulations, stratification, and smaller scale turbulence.

Finally, we used the DNS simulations reported in Holt et al (1992) and Shih et al (2000) together with laboratory experimental data from Barry et al, (2001), Rehmann and Koseff (2003), and Jackson and Rehmann (2003) to examine paramterization of the eddy diffusivity in stratified turbulent flows.

RESULTS

We ran numerical simulations of stratified channel flows for a number of different flows, varying the strength of the stratification, the type of forcing (Poiseulle, Couette, or Poiseulle-Couette), the relative position of the stratification in the water column, and the type of density boundary conditions (either constant temperature or zero flux).

Stratified Channel Flows: We were able to compute planar averaged statistics for these flows which are typically characterized by a relatively well-mixed, lower boundary region where the turbulence is quite vigorous; a thermocline region where the turbulence is strongly affected by the buoyancy forces; and an upper mixed layer which is separated from the lower boundary by the thermocline. The more weakly stratified flows (with zero flux boundary conditions) are quickly mixed, while in the more strongly stratified cases the turbulence is significantly suppressed over the entire water column. In the free-stream portion of the flows, in general, the turbulence behaves similarly, albeit not identically, to turbulence in homogeneous shear flow. The nature of the stratified turbulence is very similar to that seen in other flows. This is shown in Figure 1 where the density and turbulence profiles for three different flow cases (weak, mild, and strong stratification) are shown as a function of time. $Re_{\tau} = 360$ and the zero-flux boundary conditions are imposed.

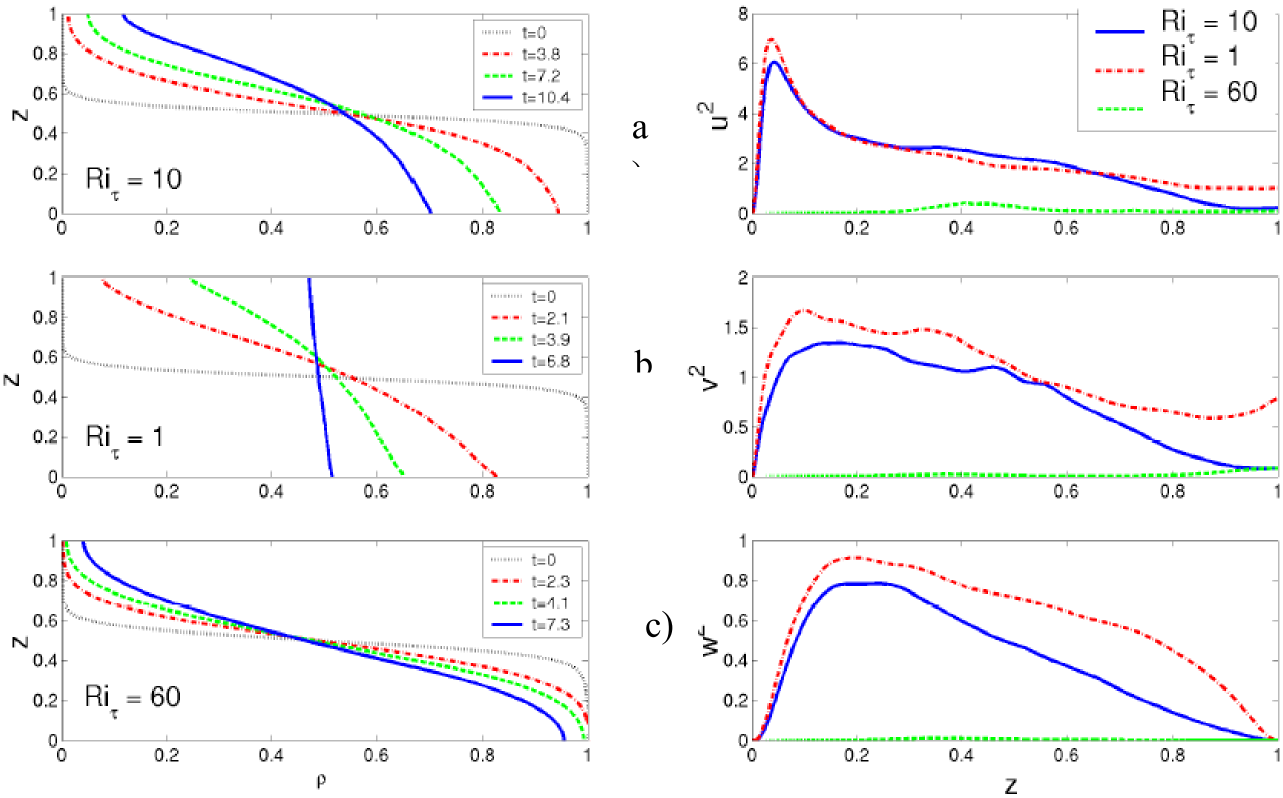

Figure 1: Time evolution of density and turbulence profiles for runs with Re_τ= 360, and a) Ri_τ = 1, b) Ri_τ = 1, and c) Ri_τ =60.

Langmuir Circulations: We have completed the simulations for a whole range of flows with Langmuir circulations using the stratified channel flows (described above) as the basis. To generate the Langmuir cells we need to apply an additional surface stress forcing. These results are currently being analyzed as part of another ONR sponsored project. We have found that the growth of Langmuir circulations is inhibited, but not completely suppressed, by stratification. The presence of the vortex forcing mechanism above a thermocline induces surface mixed layer deepening.

Stratified Shear Flows: We have used the results from our very extensive database of homogeneous, sheared, stratified turbulence to look at parameterizations of the eddy diffusivity, Kρ. W□ found that the Osborn (1980) prediction is reasonable when the turbulence is stationary ($20 < \varepsilon/\nu N^2 < 100$) but for values that are greater than 100 the diffusivity appears to be a function of $(\varepsilon/\nu N^2)^{0.5}$. Furthermore, from dimensional analysis the diffusivity requires 2 dimensionless parameters for full description: the Froude number and the turbulent Reynolds number. We found that a high Reynolds the diffusivity became independent of Reynolds number, and we were able to develop a relationship for $K\rho$ in terms of Froude number alone.

IMPACT/APPLICATIONS

The simulations completed 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. Our simulations of the channel flows are the first important step in developing a code for studying the evolution of the density structure of the water column in the near-coastal ocean. Once completed this code will be a valuable research tool for use in conjunction with field work currently underway involved in measuring flowfields in the near-coastal ocean.

TRANSITIONS

The numerical databases developed have been analyzed by the PI's in other research projects and the data has been used by researchers at other institutions. For example Diamessis and Nomura at UCSD have used the data from the simulations of Shih *et al.* (2000) to further examine the interaction between vorticity and rate-of-strain in stratified turbulence. In addition, Ivey at the Center for Water Research at the University of Western Australia, Rehmann at the University of Illinois, and Umlauf at EPFL in Switzerland, are using the data to look at parameterizations of turbulent length scales and buoyancy flux in stratified flows.

RELATED PROJECTS

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