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 wind stresses, 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 physcis, by looking at a more idealized version of this problem using a variety of numerical simulation approaches.We plan to develope Large Eddy Simulation Models of the flow structure in the stratified water column in the near-coastal zone which are typically subject to surface heating fluxes, wind stirring, and tidally generated bottom turbulence. Using these simulation tools we shall study the physics, and how to parameterize it, for two related flow problems in particular:

Stratified tidal flows, i.e., stratified flows with oscillating pressure gradients;
Wavy turbulent flows, i.e., unstratified channel flows with waves.

APPROACH

Two codes have been developed for doing the proposed simulations. The first is a parallelized Navier-Stokes code for solving stratified, turbulent channel flows. This code has been developed and has been implemented on the 400 node Intel Paragon XP/S supercomputer at SDSC. A description of the numerical method, speedup and

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performance timing measurements on Intel iPSC/860 and Paragon XP/S computers is presented in Garg et al. (1994, 1995). To test this code we performed large-eddy simulations (LES) of turbulent channel flow with a passive scalar at Reynolds number 180 (based on friction velocity and channel half-width) and Prandtl number 0.71, using the Smagorinsky and dynamic (least-squares version) subgrid-scale models.
The second code is a finite-volume Navier-Stokes code developed by Zang et al. (1994). This code has been used to succesfully simulate flow in a turbulent lid-driven cavity (Zang et al., 1993), and the upwelling process in a stratified, rotating flow (Zang and Street, 1995). It is currently being used, and will be used, for simulating a surface wave propagating over a turbulent flow.

WORK COMPLETED

1. Performed Direct Numerical Simulations (DNS) of turbulent channel flow with a passive scalar at Reynolds number 180 (based on friction velocity and channel half-width) and Prandtl number 0.71, using the Smagorinsky and dynamic (least-squares version) subgrid-scale models for a range of Richardson numbers

2 Performed Large Eddy Simulations (LES) of turbulent channel flow (using the dynamic subgrid-scale model) at Reynolds number 180, Prandtl number 0.71 and Richardson number equal to 0 (unstratified), 10, 18, 30 and 60 respectively.

3. Performed LES of turbulent, free-surface channel flow (using the dynamic subgrid-scale model) at Reynolds number 180, Prandtl number 0.71 and Richardson numbers from 0 to 165.

4. Used the results from very fine grid LES and DNS to evaluate turbulence models and examine turbulence budgets for these flows.

5. Performed simulations for the following flows related to the wavy boundary problem:

a) Inviscid flow under a second-order Stokes wave
b) Laminar two-dimensional flow under a wavy surface
c) Laminar two-dimensional flow with a Craik-Leibovich forcing term

RESULTS

Results from the simulations of the stratified channel flow are as follows:

a) Flows can be classified as “buoyancy affected” or “buoyancy controlled” depending on the value of the Richardson number of the flow. The transition Richardson number is a function of the Reynolds number of the flow: this result is consistent with that of Holt et al. (1992).

b) Our analysis of the stratified closed-channel flow simulations allows us to construct a pathway via which stratification affects the turbulence. The pathway is as follows: stable density gradients affect the near-wall processes (by destroying the near-wall coherent structures and thereby disrupting the burst-sweep process), reducing the generation of Reynolds shear-stress and turbulence production. This leads to decreased vertical transport, thereby weakening the coupling between the inner and outer regions of the flow. The reduced turbulence production and transport decrease the turbulent kinetic energy (TKE); since the energy generation at the large scales sets the viscous dissipation rate the dissipation of the TKE is also suppressed. The decreased turbulence levels also cause the mean flow to respond such that the flow rate increases and the mean shear is altered.

c) Under some conditions the decoupling of the inner and outer regions led to relaminarization of the flow.

d) The local gradient Richardson number is not a good descriptor of the state of the flow. By analyzing the values of Ri in the wall-region (order of 10^{-3} to 10^{-2}) one would expect the turbulence to be relatively unaffected by the stratification. As stated in a) above this is certainly not the case in the near-wall region.

e) The peak mixing efficiency occurred in regions of the flow where the local Froude number was around 1 in agreement with data from our other stratified flow experiments and simulations.

f) For the free-surface flows examination of the energy spectra showed the quasi two-component nature of the flow in the vicinity of the free-surface. In some cases the presence of stratification and resultant collapse of the turbulence results in linear internal waves near the free-surface.

g) Our evaluation of turbulence models for these flows shows that (i) gradient-diffusion models for turbulent transport have difficulty, (ii) anisotropic models work better than isotropic models, (iii) pressure-transport is an important term in free-surface flows and cannot be lumped with turbulent transport, and (iv) accurate modeling of the scalar pressure-gradient correlation is essential in stratified flows.

Results from the simulations of the stratified channel flow are as follows:

a) For the case of the inviscid flow under a second-order Stokes wave, the predicted flow using the computational model is in very good agreement with the second order theory we developed. As expected, the difference between the simulation and the theory is in the order of the cube of wave slope. Moreover, the simulation also gives a Stokes drift that matches the linear theory.

b) For the case of the two-dimensional laminar flow under a wavy surface we developed and implemented a stress boundary condition for the top surface in the curvilinear system, which allows us to specify a tangential stress along the wavy surface. The introduction of viscosity results in a viscous boundary layer under the wavy surface and spanwise vorticity near the top surface. This vorticity diffuses inward and is responsible for a mass transport other than Stokes drift. The Eulerian mean velocity is predicted for cases of different Reynolds number, and the results scale well with Longuet-Higgins' solution for high Reynolds number flow: the predictions give results that asymptotically approaches Longuet-Higgins theory with increasing Reynolds number.

c) The computational model was further verified by simulating a laminar “3D” flow in a rectangular physical domain. The Craik- Leibovich equations with vortex forcing are solved. The flow field is assumed to be invariant in the streamwise direction. The base flow contains a streamwise mean current with constant shear and a linear Stokes drift. The initial condition is small magnitude white noise from a random number generator and the code solves for the three components of velocity disturbances. The spanwise dimension is chosen as one wavelength of the dominant unstable mode for the specific Rayleigh number of the mean flow, which is given by a linear stability theory. Two counter-rotating cells can be observed from the vorticity plot. The results also exhibits several key properties of Langmuir Circulation:

The structure of the cell is asymmetric. The maximum downwelling velocity is greater than the upwelling velocity.
A current anomaly is also observed. The wind-directed surface current has maximum magnitude above the convergence zone.

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 data-bases developed have been analysed by the PI’s in other research projects and the data has been used by researchers at other institutions.

RELATED PROJECTS

A Study of the structure of stratified flows - NSF - (Monismith PI)

The structure of turbulence and other motions beneath an air-water interface - ONR - (Monismith Co-PI)

An Experimental Study of a Breaking Interfacial Wave - NSF- (Koseff PI)

Chemical Sensing in the Marine Environment -ONR - (Monismith PI)

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