Laboratory Benchmarks for the Development of Numerical Ocean Models

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LONG-TERM GOAL

The long-term goal of this project is to assess the feasibility of using laboratory models of turbulent coastal flows to develop improved parameterizations for oceanic boundary turbulence, thus contributing to the improvement of predictive coastal ocean models.

SCIENTIFIC OBJECTIVES

The scientific objective of this research is to understand the impact of boundary turbulence on coastal circulation in the absence and presence of topographic features such as submarine canyons. The near-term objectives include: (i) to check experimentally if boundary turbulence, at values of the system parameters relevant to the coastal oceans, alters the velocity and density fields; (ii) to obtain a better understanding of turbulent boundary layers associated with currents along sloping surfaces in rotating stratified flows; and (iii) to utilize laboratory data to test current parameterizations used in numerical coastal models.

APPROACHES

The physical system considered is given schematically in Figure 1. In particular we investigate the flow fields developed by along-shelf oscillatory currents (to simulate along-shelf tides) and up- and down-welling favorable impulsive currents (to simulate wind-driven flows) in an annular geometry both in the presence and absence of an isolated canyon. The model considers both rotation and stratification, and the principal focus of this project is on turbulent flows generated either naturally or forced by the introduction of surface roughness elements.

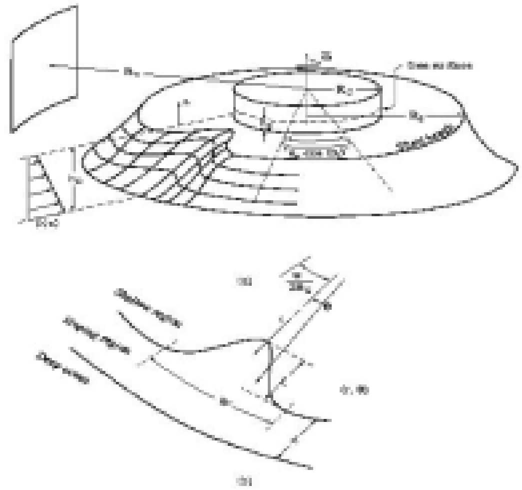


Figure 1. Physical System

The early experiments (laminar) in this coupled laboratory-numerical modeling project were carried out in a rotating test facility 1.8 m in diameter and 20 cm deep. The more recent experiments in which turbulence plays an important role were conducted on the Coriolis rotating platform in Grenoble, France. The Grenoble platform is 14 m in diameter and supports a 13-meter diameter circular fiberglass tank used as the test cell. Topographic models of the shelf, shelf break and continental slope were placed in the center of the test cell (see Figure 1). In some of the Grenoble experiments, the entire shelf, shelf break and continental slope (including the canyon area) were covered by cubic roughness elements. The resulting flow fields are measured primarily using correlation image velocimetry (CIV). The dimensionless parameters for the ASU and Grenoble experiments are delineated in Tables 1.

The numerical simulations were conducted at IMCS and have utilized two different models -- the Spectral Element Ocean Model (SEOM) and the Regional Ocean Modeling System (ROMS). The two models differ primarily in their differing approaches to spatial discretization (high-order finite element and low-order finite difference, respectively), but are terrain-following so that in principle both should offer convergent solutions to flow problems featuring strong topographic variations and stratification. Haidvogel and Beckmann (1999) give a concise description of both model classes.

Table 1. Dimensionless parameters

	ASU-PHB	**Grenoble OP1**	**Grenoble OP2**
h_S/h_D (fractional depth)	0.20	0.20	0.20
d/h_d (normalized roughness); 0.0 smooth	0.00	0.0, 0.033	0.0, 0.033
h_D/W (vertical aspect ratio)	0.63	0.63	0.63
W/L (horizontal aspect ratio)	1.33	1.33	1.33
$Bu=(N^2h_D^2)/(f^2W^2)$ (Burger number)	9.8	9.8	1.36
$E=\nu/(fh_S^2)$ (Ekman number)	$(3.2)\ 10^{-3}$	$(3.0)\ 10^{-4}$	$(1.0)\ 10^{-4}$
$Ro_t=(2\pi/T)/f$ (temporal Rossby number)	0.52	0.52	0.5
$Re_d=u_0d/\nu$ (Reynolds number, roughness)	-	0; 400	0; 1500
Ro=U/(Fw) (Rossby number)	0.10	0.10	0.14
X/W = (normalized forcing excursion)	0.38	0.38	0.55

WORK COMPLETED

A manuscript (Haidvogel, 2002) has been completed on (i) the cross-shelf transport of material, (ii) the associated parametric dependencies, and (iii) the energy budget in the vicinity of the isolated canyon. A second manuscript by Boyer, Haidvogel and Perenne (2002) is almost completed and addresses the reasons for the discrepancies between the numerical runs and the laboratory results in the Perenne et al. (2001) paper; this manuscript also explores the sensitivity of a number of flow observables to variations in several of the most significant parameters. With the completion of these studies, the laminar flow data sets obtained some years ago will have been fully exploited.

The remaining efforts have focused on the effects of the boundary turbulence on the no-canyon and canyon flows. A second experimental series was completed during the period January-March 2002. These experiments addressed the nature of the flow fields obtained under conditions in which boundary turbulence is generated by impulsive upwelling- and downwelling-favorable flows for both the case of pure azimuthal shelf-slope topography and the same topography incised by a single canyon. Those experiments have been completed and the data are now being analyzed. Manuscripts on these no-canyon and canyon studies by Srdic-Mitrovic *et al.* (2003a) and Srdic-Mitrovic *et al.* (2003b), respectively, are presently being prepared and will be submitted for publication in early 2003.

RESULTS

Laminar Flows

Motivated by the early results for laminar flows (Perenne *et al*., 2001), Haidvogel (2002) conducted a laboratory-scale numerical analysis of the cross-shelf transport of mass in the vicinity of the canyon as well as an analysis of the kinetic and potential and kinetic energy budgets for the shelf and canyon regions. It is shown that the incident oscillatory currents produce, in equilibrium, an extensive pool of anomalously dense fluid on the shelf surrounding the canyon. The net on-shelf transport of dense water varies linearly with forcing period (inverse temporal Rossby number) and quadratically with forcing strength (Rossby number). Variations in on-shelf pumping with Burger number are found to be weak. An analysis of kinetic and potential energy budgets for the shelf and canyon regions reveals an energy cycle characterized by: production of kinetic energy within the canyon by the oscillating currents; conversion of kinetic energy to potential within the canyon; advective export of potential energy from the canyon to the shelf; conversion of potential energy back to kinetic on the shelf; and dissipative loss along the way which importantly includes internal viscous loss, lateral diffusion and bottom friction. While pressure work redistributes kinetic energy within the shelf/canyon system at locally high rates, very little net energy is exported away from the immediate region of the dense pool.

Boyer, Haidvogel and Perenne (2002) show that if all parameters are fixed with the exception of the Burger number, Bu, that smaller Bu (smaller stratification) leads to more intense rectified flows; this owes to the tendency for the oscillating current to advect over longer traverses (and hence to increase any rectified currents). The Perenne et al. 2001 study revealed that the magnitudes of the residual flows found in the laboratory were significantly different than those simulated by the numerical model. The determination of the reason for this discrepancy was thus addressed. Our joint work has also shown that the use of a constant stress law along the floor rather than one that more accurately depicts the boundary layer along the model floor led to the numerical-laboratory model differences. It is

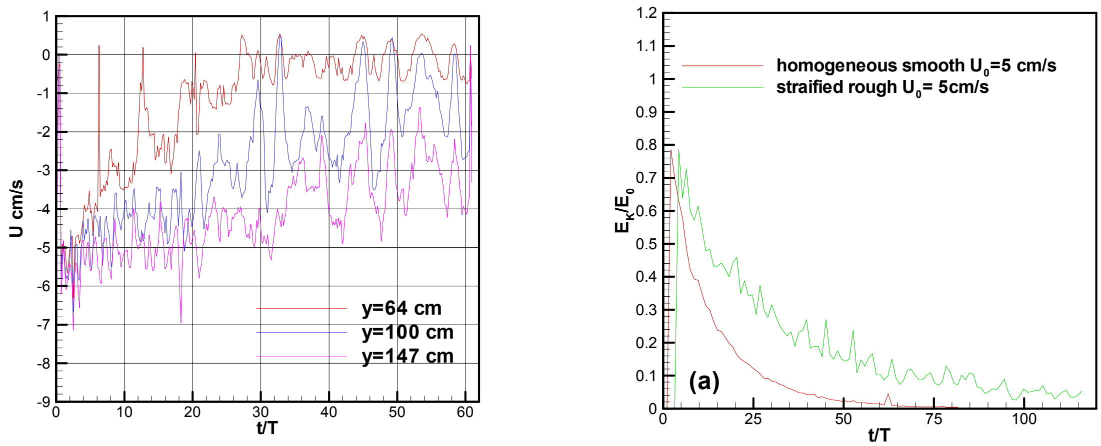


Figure 2: (a) The average kinetic energy for the impulsively started downwelling favorable flow over continuous topography. (b) Along-shelf velocity component obtained at the shelf- break level for the no-canyon case.

concluded that significant attention should be given to the general application and parameterization of the lower boundary condition for the turbulent flow cases presently being investigated.

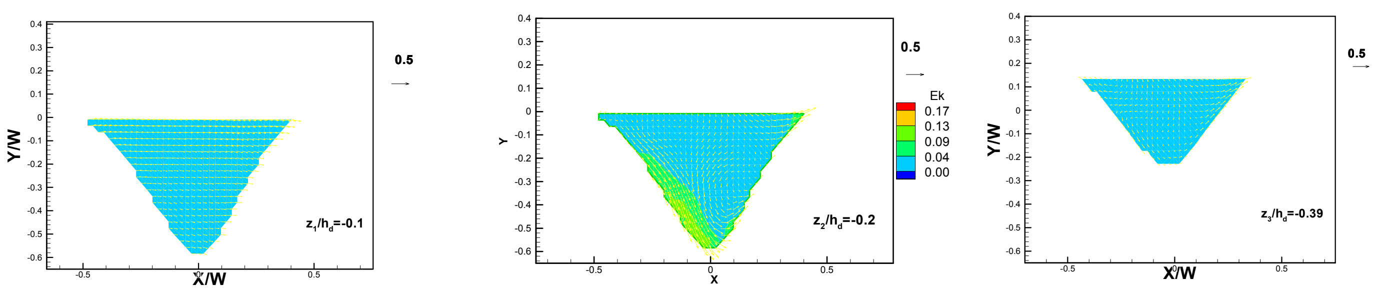
Turbulent Flows

The principal focus of the past year's work has been on the effects of boundary turbulence on flows along the continental shelf and slope, both in the presence and absence of a canyon. In order to assess the nature of the flow in the Grenoble test facility in the absence of a canyon, experiments were run for both a homogeneous fluid and a linearly stratified one for both upwelling and downwelling (spin-up) favorable flows at the parameter values indicated in Table 1. Figure 2a is a plot of the normalized average kinetic energy per unit mass for a downwelling favorable flow for a region of the flow encompassing the shelf break and extending to the outer edge of the tank. One notes that the homogeneous case decays relatively rapidly and is quite smooth indicating that no large-scale eddies are advecting through the control surface being monitored. The flow thus appears to be barotropically stable.

The decay plot (Figure 2a) for the stratified case is dramatically different than that for the homogeneous case. The data show large variations in the kinetic energy within the control volume as a function of time. This owes to the formation of advecting eddy structures that move through the control surface being monitored. An alternative way of observing these instabilities is to depict the horizontal components of the Eulerian velocity from the CIV records at a series of points along a radius of the test cell. Figure 2b is a plot of the cross-shelf velocity component at the three radii indicated. The shelf break is at y = 45 cm. One notes that the instabilities in the flow begin almost immediately and have the frequency of the turntable. As time progresses, the eddies associated with these instabilities merge, leading to flow structures of larger horizontal extent. These and other data confirm that these signatures are of basin-scale cyclones advecting around the test cell. The counterpart upwelling-favorable flows similarly show that the barotropic cases are stable and the baroclinic cases unstable, with the latter associated with advecting anticyclones. All of the barotropic experiments were found to be stable and all of the baroclinic ones unstable.

The data taken during January and February 2001 in Grenoble on oscillatory along-shelf turbulent flow in the vicinity of an isolated canyon has been analyzed and a manuscript by Boyer *et al.* (2002) is almost complete. Owing to background rotation effects, mean flows are generated for all of the experiments and these are generally characterized by boundary currents along the canyon walls, which are in a direction with the shallow topography on the right facing downstream. Experiments conducted at small but different Ekman numbers, other parameters being fixed, show that small Ekman numbers should not be associated with flows having negligble friction. The experiments also demonstrate that the introduction of boundary turbulence, other parameters being fixed, leads to weaker residual motions. Numerical simulations using the SEOM model are underway but definitive results are not yet available.

Figures 3a,b,c depict the residual velocity fields and normalized kinetic energy distributions for the respective levels for a smooth canyon at the parameter values OP1 (Table 1); here (a) mid-depth at the fluid level above the shelf, (b) the shelf break and (c) one quarter of the distance from the shelf break to the model floor. The blue region represents the area between the shallow edge of the canyon to a line joining the edges of the canyon. The color chart is for the normalized (by the square of the maximum speed of the forcing flow at the shelf break) kinetic energy at each of the levels. This illustration shows, among numerous other things, that the residual motion is strong throughout the water column and that its characteristic value becomes stronger with depth, at least to the one-quarter distance to the model floor. This is in sharp contrast to laminar flows for which the residual flow is markedly strongest at the level of the shelf break and decreases rapidly both above and below this level.



(a) *(b)* *(c)*

Figure 3: Normalized kinetic energy distribution for the smooth canyon.

IMPACT/APPLICATION

There is increasing interest, related to both military and civilian needs, in predictions of currents, temperature and salinity fields in the coastal zone. Meeting this goal will require the development of more reliable numerical models for the coastal zone. Owing to the fact that detailed measurements in space and time for testing coastal ocean models are often lacking, this project seeks to use carefully designed laboratory experiments, which include turbulence, to serve as data sources in the improvement of numerical models of the coastal zone.

TRANSITION

As noted below, Dr. Haidvogel is developing a website of test problems for numerical ocean models. The results of the present experiments, as well as those for the laminar flows addressed earlier, will be placed on that website so that all interested numerical modelers will have easy access to the laboratory data.

RELATED PROJECTS

Under separate funding from ONR, one of the PI's (Haidvogel) and his colleagues are developing a World Wide Web site containing a variety of analytic, quasi-analytic and geophysical test problems for ocean models. One of the geophysical test problems currently being formulated for deployment on the web site is the central laboratory experiment of Perenne *et al*. (2001b). As described above, we now have (or will shortly have) replicate simulations obtained with both SEOM and ROMS for this case.

REFERENCES

Haidvogel, D.B. and Beckmann, A. numerical ocean circulation modeling, Inperial College Press, 1999.

Pérenne, N., D.B. Haidvogel and D.L. Boyer, 2000a: Laboratory - numerical model comparisons of flow over a coastal canyon. *J. ATM. Ocean. Tech*., 18(2), 235-255.

PUBLICATIONS

Boyer, D. L. and Srdic-Mitrovic, A. N., 2002: Laboratory experiments of continuously stratified flows past obstacles, Environmental Stratified Flows, Editor: Roger Grimshaw, Kluwer Academic Publishers.

Boyer, D. L., Haidvogel, and Perenne, N. 2002: Laboratory numerical models comparisons of canyon flows: A parameter study. To be submitted to J. Phys. Ocean.

Boyer, D. L., Srdic-Mitrovic, A. N., Haidvogel, D. B., Levine, J. and Sommeria, J., 2002: The effect of boundary turbulence on canyon flows forced by periodic, along shelf-currents. To be submitted to J. Phys. Ocean.

Haidvogel, D.B., 2002: Cross-shelf exchange driven by oscillatory barotropic currents over an isolated coastal canyon: Equilibrium circulation and dynamics. To be submitted to J. Geophys. Res.

Srdic-Mitrovic, A. N., Boyer, D.L., Etling, D., and Sommeria, J., 2001: Laboratory observations of flows near submarine canyon. Submitted to 3rd International Symposium on Environmental Hydraulics, Tempe

Srdic-Mitrovic, A. N., Smith IV, D., Boyer, D. L., Smirnov, S. and Sommeria. J., 2003a: On the spin-up and spin-down of flow along a continuous shelf-continental slope in a cylindrical test cell. In preparation.

Srdic-Mitrovic, A. N., Smith IV, D., Boyer, D. L., and Sommeria. J., 2003b: On the spin-up and spin-down of flow along a shelf-continental slope interrupted by a single canyon. In preparation.