Modeling Non-Hydrostatic Flow Over Topography

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LONG-TERM GOALS

The long-term goal of this research is to facilitate physically motivated parameterization of small-scale physics in practical ocean forecast models. It is envisioned that broad application of robust, easy-to-use simulation tools in which non-hydrostatic physics is directly resolved will provide a framework within which parameterization schemes can be formulated and quantitatively evaluated.

OBJECTIVES

The primary aim of this proposal is to refine an existing set of numerical tools for the simulation of non-hydrostatic flow over rough topography, to undertake a series of validation and demonstration simulations using these tools, and to make the tools themselves, their configuration scripts and documentation available to the community at large via the web.

APPROACH

This modeling effort employs efficient, high-order numerical techniques on parallel computers to solve the non-hydrostatic equations of motion for stratified flow in the presence of irregular topography. It represents a merger and compromise between two separate lines of code development. The first is based on spectral methods for turbulent stratified flows in the absence of boundary effects while the second uses curvilinear, boundary fitting coordinates along with implicit, compact differentiation schemes. In this effort, the underlying numerical grid is Cartesian with the boundaries represented independently using immersed boundary techniques. A configurable mix between spectral and compact differentiation is used in combination with fourth order accurate time stepping.

Harvey Seim (University of North Carolina), Don Slinn (University of Florida), Pascale Lelong and Bob Robins (Northwest Research Associates, Bellevue WA), Bill Smyth (Oregon State University), and Miles Sundermeyer (University of Massachussetts, Dartmouth) have all contributed substantially to this effort by applying different versions of the models to their application problems and communicating strengths, weaknesses and problems back to me.

WORK COMPLETED

Several tasks of a technical nature have been accomplished in the first fiscal year of this project. A brief summary is given below.

1. Generalized representation of topography: Early implementations of the code assumed that the topographic height varied only in one spatial coordinate. This was a necessary simplification for the boundary fitting grid approach where a curvilinear, orthogonal mapping between spatial and computational coordinates was required. It was introduced purely for programming convenience and for ease of testing in the immersed boundary code. Specifying the bottom topography is now accomplished within a single user-defined subroutine that prescribes the height of the topography *h(x,y)*, relative to some reference level, given an arbitrary horizontal location *(x,y)*. The sampling requirements for the topographic representation are internally calculated; the user need only specify a continuous form. Similarly, the domain decomposition and the consequent mapping of the immersed boundary points to different processors is internally generated and shielded from the user.

2. Spectral-differentiation: User configurable switches are now in place to permit spectral differentiation whenever appropriate. The spectral routines from the original codes have been upgraded to use the FFTW routines from MIT, which have been tuned for a wide variety of architectures and are generally the fastest portable routines available. Using immersed boundary techniques, it is often possible to define the computational domain in such a way that "dead-zones" or regions of now flow can be tied together with periodicity conditions while the interior flow of interest exhibits no such structure. This permits the accuracy of spectral differentiation schemes to be employed for seemingly non-periodic flows.

3. Direct solver for pressure: Generally, a three-dimensional elliptic equation needs to be solved for pressure at each time step in a non-hydrostatic code. This portion of the algorithm is both expensive and demanding in the sense that errors and inaccuracies can lead to unacceptable degradation of the overall solution. I have coded up a parallel implementation of a multi-grid iterative solver for the generalized elliptic equation required. To date, this approach has proven unsatisfactory for problems characterized by large spatial aspect ratios. For these problems, convergence occurs either too slowly to be practical or does not occur at all. For problems amenable to spectral methods in the horizontal however, a far more efficient solution is available. For these problems, the horizontal portion of the problem can be solved semi-analytically, i.e. using discrete Fourier transformations, leaving only a one-dimensional problem that needs to be solved numerically. It is feasible and efficient to solve this 1d problem directly, i.e. by forming and factoring the matrix explicitly outside of the main time stepping loop. This approach has now been coded and tested and is implemented automatically if the appropriate periodic structure of the computational domain is detected.

4. Port to several machines: The codes have been ported, tested and run on several different parallel architectures including three different Cray T3E environments, an Athlon Beowulf cluster with Myrinet, a PIII Beowulf cluster with Myrinet, an Alpha cluster with Ethernet and serial workstations running Linux.

5. Adiabatic immersed boundary conditions: There are many approaches to handling the boundary conditions prescribed on the immersed boundary. Generally, a subsidiary problem is solved for a field of forces that are to be applied to the fluid at grid points in the vicinity of the boundary. The strength of these forces is calculated so that when applied, the fluid is brought to rest at the immersed boundary. A similar approach has been developed for handling the adiabatic condition for scalars. A set of control points, just below the immersed boundary is defined. These points represent locations for sources or sinks of heat with prescribed spatial decay characteristics, i.e. a localized hot spot that decays like a Gaussian in each space dimension. At each time step, the values of the scalar field at the grid points are interpolated to the immersed boundary points. These values are then used to determine approximately,

whether the temperature values at the control points should be increased or decreased to guide the solution toward satisfaction of the boundary conditions.

6. Parallelized LES closure: The present implementation is based on strait-forward Laplacian dissipation and diffusion. An earlier version had the option of a stratified-form of the Smagarinsky LES closure. Work is ongoing but not completed to provide a wider variety of SGS closure options.

RESULTS

A version of the immersed boundary method was combined with spectral and 6th order compact differentiation schemes in an algorithm for stratified, rotating flow in the presence of irregular application of the boundary conditions at the topography *z=h(x,y)* as opposed to applying a linearized

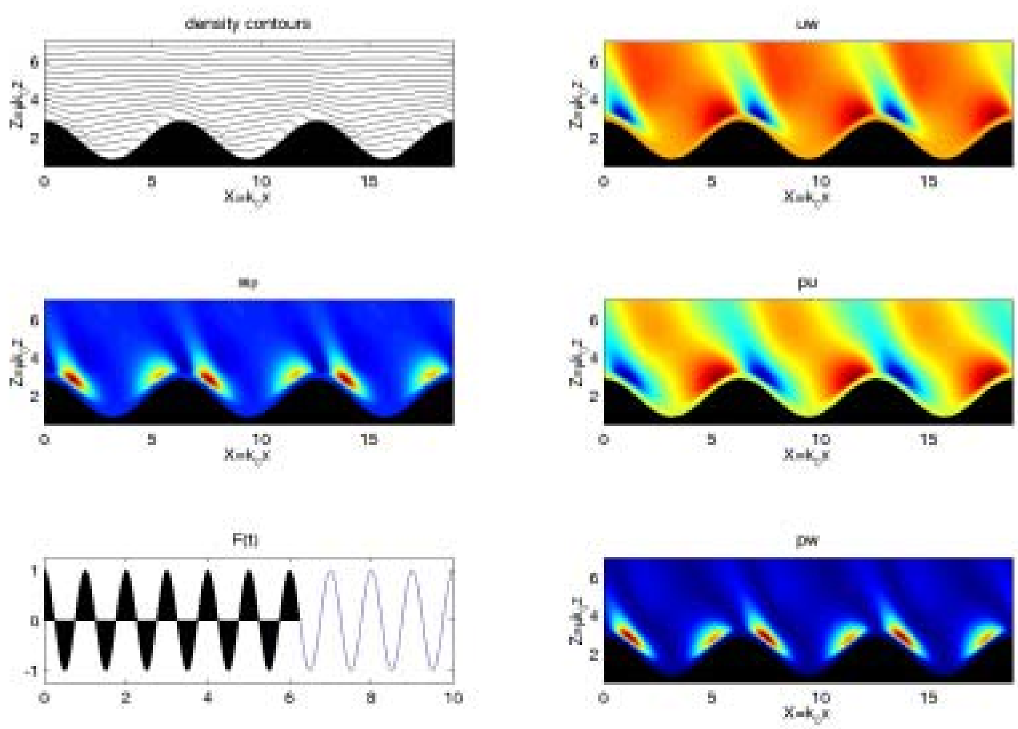

Figure 1: Instantaneous view of generation of internal tide at horizontal scale $2\pi/k_0$=2500m at critical slope. The bottom left panel shows the phase of the forcing at the time of the snapshot.

condition at *z=0* appears to be important for finite amplitude topography.
Figure (1) shows a snapshot of various correlations in an *x-z* plane for oscillatory flow over a corrugated bottom at critical slope (wave angle matches topographic slope). Several differences are apparent in comparison with recent analytical work on internal tide generation. In particular,

Figure (2) illustrates the implementation of the immersed boundary approach for an adiabatic condition on density. Figure (2a) shows the density perturbations in an x-z plane along with an immersed boundary defining a channel extending into the plane of the figure. The snapshot is taken shortly after startup in a simulation where an along-channel, geostrophically balanced flow adjusts to the presence

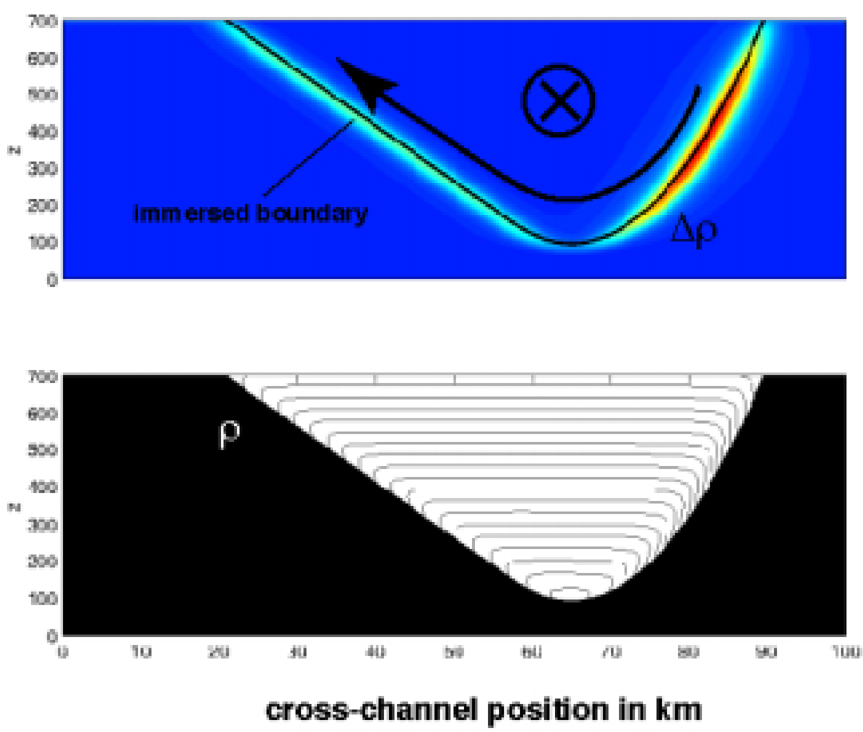

Figure 2. Upper panel (a) shows the density perturbation from a linear profile, emphasizing the heat source just below the immersed boundary. Lower panel (b) shows the total density field that satisfies the required adiabatic condition. The vertical coordinate is in meters.

of no-slip channel walls by establishing a cross-channel circulation. At the time of the snapshot, the cross-channel flow is weak and shown only schematically by the arrow. The initial density field was consisted of a linear profile in z, thus violating the required condition of no normal gradient at a curving boundary. The immersed boundary treatment detects this flaw and introduces heat sources below the immersed boundary such that the density boundary conditions are quickly and continuously maintained. Figure 2(b) shows the total density field satisfying the adiabatic boundary condition. (Note the large horizontal to vertical aspect ratio. Though the right-to-left near bottom flow is only just being spun up, its presence is detectable as an asymmetry in the density contours just above the boundary.)

The region below (or to the outside) the immersed boundary constitutes a “dead-zone” of no flow. This permits the use of periodic computational boundary conditions and hence spectral differentiation and a direct solution method for pressure.

IMPACT/APPLICATIONS

It is the intent of this work that high-resolution, non-hydrostatic process modeling will become accessible to those analyzing data and or running larger-scale ocean models and will aid the ongoing development of physically-based parameterization schemes for these models.

TRANSITIONS

Several groups are using the codes, at different stages of development for their own scientific applications. In addition, the NASA Office of Earth Science has funded a three-year grant entitled Ocean Mixing from Shear Deformation of Ice Leads: An Important Component of the Surface Heat Budget of the Polar Oceans (PI Max Coon, NWRA) which will use this model on the T3E at ARSC.

PUBLICATIONS

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