A Community Terrain-Following Ocean Modeling System (ROMS/TOMS)

Hernan G. Arango
Institute of Marine and Coastal Sciences, Rutgers University
71 Dudley Road
New Brunswick, NJ 08901-8521, USA
Phone: (732) 932-6555 x266 Fax: (732) 932-6520 email: arango@marine.rutgers.edu

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LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation, primitive equation ocean model for high-resolution scientific (ROMS: Regional Ocean Modeling System) and operational (TOMS: Terrain-following Ocean Modeling System) applications. This project will improve the ocean modeling capabilities of the U.S. Navy for relocatable, coastal, coupled atmosphere-ocean forecasting applications. It will also benefit the ocean modeling community at large by providing the current state-of-the-art knowledge in physics, numerical schemes, and computational technology.

OBJECTIVES

The main objective is to produce a tested expert ocean-modeling framework for scientific and operational applications over a wide range of spatial (coastal to basin) and temporal (days to seasons) scales. The primary focus is to implement the most robust set of options and algorithms for relocatable coastal forecasting systems nested within basin-scale operational models for the Navy. The system includes some of the analysis and prediction tools that are available in Numerical Weather Prediction (NWP), such as: 4-dimensional variational data assimilation (4D-Var), ensemble prediction, adaptive sampling, and circulation stability and sensitivity analysis.

APPROACH

The structure of TOMS is based on ROMS because of its accurate and efficient numerical algorithms, tangent linear and adjoint models, variational data assimilation, modular coding and explicit parallel structure conformal to modern computer architectures (both cache-coherent shared-memory and distributed cluster technologies). Currently, both ROMS and TOMS are identical and continue improving and evolving. ROMS remains as the scientific community model while TOMS becomes the operational community model.

ROMS/TOMS is a three-dimensional, free-surface, terrain-following ocean model that solves the Reynolds-averaged Navier-Stokes equations using the hydrostatic vertical momentum balance and Boussinesq approximation (Haidvogel *et al.* 2000, 2008; Shchepetkin and McWilliams, 2005, 2009).

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The governing dynamical equations are discretized on a vertical coordinate that depends on the local water depth. The horizontal coordinates are orthogonal and curvilinear allowing Cartesian, spherical, and polar spatial discretization on an Arakawa C-grid. Its dynamical kernel includes accurate and efficient algorithms for time-stepping, advection, pressure gradient (Shchepetkin and McWilliams 2003, 2005), several subgridscale parameterizations (Durski *et al*., 2004; Warner *et al*., 2005) to represent small-scale turbulent processes at the dissipation level, and various bottom boundary layer formulations to determine the stress exerted on the flow by the bottom.

Several adjoint-based algorithms exist to explore the factors that limit the predictability of the circulation in regional applications for a variety of dynamical regimes (Moore *et al*., 2004, 2009). These algorithms use the ideas of Generalized Stability Theory (GST) in order to identify the most unstable directions of state-space in which errors and uncertainties are likely to grow. The resulting singular vectors can be used to construct ensembles of forecasts by perturbing initial and boundary conditions (optimal perturbations) and/or surface forcing (stochastic optimals). Perturbing the system along the most unstable directions to the state-space yields information about the first (ensemble mean) and second (ensemble spread) moments of the probability density function. Given an appropriate forecast skill measure, the circulation is predictable if low spread and unpredictable if large spread.

ROMS/TOMS uniquely supports three different 4D-Var data assimilation methodologies (Moore *et al.*, 2011a, b): a primal form of the incremental strong constraint 4D-Var (I4D-Var), a strong/weak constraint dual form of 4D-Var based on the Physical-space Statistical Analysis System (4D-PSAS), and a strong/weak constraint dual form of 4D-Var based on the indirect representer method (R4D-Var). In the dual formulations, the search for the best ocean circulation estimate is in the subspace spanned only by the observations, as opposed to the full space spanned by the model as in the primal formulation. Although the primal and dual formulations yield identical estimates of the ocean circulation for the same *a priori* assumptions, there are practical advantages and disadvantages to both approaches (Moore *et al.*, 2011a, b, c). To our knowledge, ROMS/TOMS is the only open-source, ocean community-modeling framework supporting all these variational data assimilation methods and other sophisticated adjoint-based algorithms.

There are several biogeochemical models available in ROMS. In order of increasing ecological complexity these include three NPZD-type models (Franks *et al.*, 1986; Powell *et al.*, 2006; Fiechter *et al.*, 2009), a nitrogen-based ecosystem model (Fennel *et al.*, 2006, 2008), a Nemuro-type lower level ecosystem model (Kishi *et al*., 2007), and a bio-optical model (Bissett *et al.*, 1999).

ROMS includes a sediment-transport model with an unlimited number of user-defined cohesive (mud) and non-cohesive (sand) sediment classes (Warner *et al.*, 2008). Each class has attributes of grain diameter, density, settling velocity, critical stress threshold for erosion, and erodibility constant. A multi-level bed framework tracks the distribution of every size class in each layer and stores bulk properties including layer thickness, porosity, and mass, allowing the computation of bed morphology and stratigraphy. Also tracked are bed-surface properties like active-layer thickness, ripple geometry, and bed roughness. Bedload transport is calculated for mobile sediment classes in the top layer.
ROMS is a very modern and modular code written on F90/F95. It uses C-preprocessing to activate the various physical and numerical options. The parallel framework is coarse-grained with both shared-memory (OpenMP) and distributed-memory (MPI) paradigms coexisting in the same code. Because of its construction, the parallelization of the adjoint is only available for MPI. Several coding standards

have been established to facilitate model readability, maintenance, and portability. All the state model variables are dynamically allocated and passed as arguments to the computational routines via dereferenced pointer structures. All private arrays are automatic; their size is determined when the procedure is entered. This code structure facilitates computations over nested grids.

WORK COMPLETED

A complete overhaul of the ROMS/TOMS 4D-Var data assimilation capabilities was done in FY09. In FY10, we concentrated on developing and testing additional algorithms for 4D-Var observations impact, observations sensitivity, array modes, and posterior error covariance analysis. Some of these developments required the adjoint of the 4D-Var data assimilation system, denoted as $(4DVar)^T$. Currently, $(4DVar)^T$ is only available for the dual formulation algorithms (4D-PSAS and R4D-Var) because the adjoint of the Lanczos-based, conjugate gradient algorithm used in the minimization is much simpler. This capability is challenging in I4D-Var due to the complexity of the I/O intensive, Lanczos-based, conjugate gradient and preconditioning algorithms that are used when the minimization is carried out in model space. We are planning to build $(I4D\text{-}Var)^T$ in the future.

The observation impact algorithm can be used to quantify the contribution of each observation during a 4D-Var analysis to a specified aspect (scalar function, say $\boldsymbol{I}$) of the ocean circulation (Langland and Baker, 2004; Gelaro and Zhu, 2009; Trémolet, 2008; Moore *et al.*, 2011c). That is, it identifies the part of the model space that controls $\boldsymbol{I}$ and that is activated by the observations. It yields the actual contribution of each observation to the circulation increment.

The observation sensitivity is based on $(4D\text{-}Var)^T$ and quantifies the change that would result in the circulation estimate as result of changes in the observations or observation array (Trémolet, 2008; Moore *et al.*, 2011c). It is a very useful tool for efficient generation of observation system experiments (OSEs), observation array design, and adaptive sampling. It can also be used to predict the changes that will occur in $\boldsymbol{I}$ in the event of a platform failure or a change in the observation array (Moore *et al.*, 2011c).

The array modes of the stabilized representer matrix can be used to determine the most stable component of the circulation with respect to changes in the innovation vector (Bennett, 1985; Moore *et al.*, 2011c). The array modes are independent of the observation values and depend only on the observation locations, the *prior* covariances, and *prior* circulation.

A ROMS training and a numerical ocean modeling workshop was held at the Hong Kong University of Science and Technology (HKUST), Honk Kong, China, in collaboration with Dale Haidvogel (Rutgers), Kate Hedstrom (University of Alaska), and Jianping Gan (HKUST) from January 5-14, 2011.

RESULTS

Three types of nesting capabilities have been designed in ROMS: (i) *refinement* grids which provide increased resolution (3:1, 5:1, or 7:1) in a specific region; (ii) *mosaics* which connect several grids along their edges, and (iii) *composite* grids which allow overlap regions of aligned and non-aligned grids. The *mosaic* and *composite* grid code infrastructures are identical. The differences are geometrical and primary based on the alignment between adjacent grids. All the *mosaic* grids are exactly aligned with the adjacent grid. In general, the *mosaic* grids are special case of the *composite* grids.

An example of *refinement* nested-grids is shown in Fig. 1 for the Monterrey Canyon system with increasing horizontal resolution. The nested grids are imbedded in a regional, eddy resolving grid of the US west coast (Fig. 1a) with an average resolution of 7.5km. The intermediate grid (Fig. 1b) has an average resolution of 2.5km and it is primarily used to simulate the submesoscale circulation from north of Point Conception to Point Arenas. The refinement ratio is 1:3. A fine-resolution grid of Monterrey Bay is shown in Fig. 1c with an average resolution of 500m and is used to study the complex canyon circulation. The grid 1c has a 5:1 refinement ratio from 1b. This type of grid nesting has been available to atmospheric models for several years and more recently to ocean models.

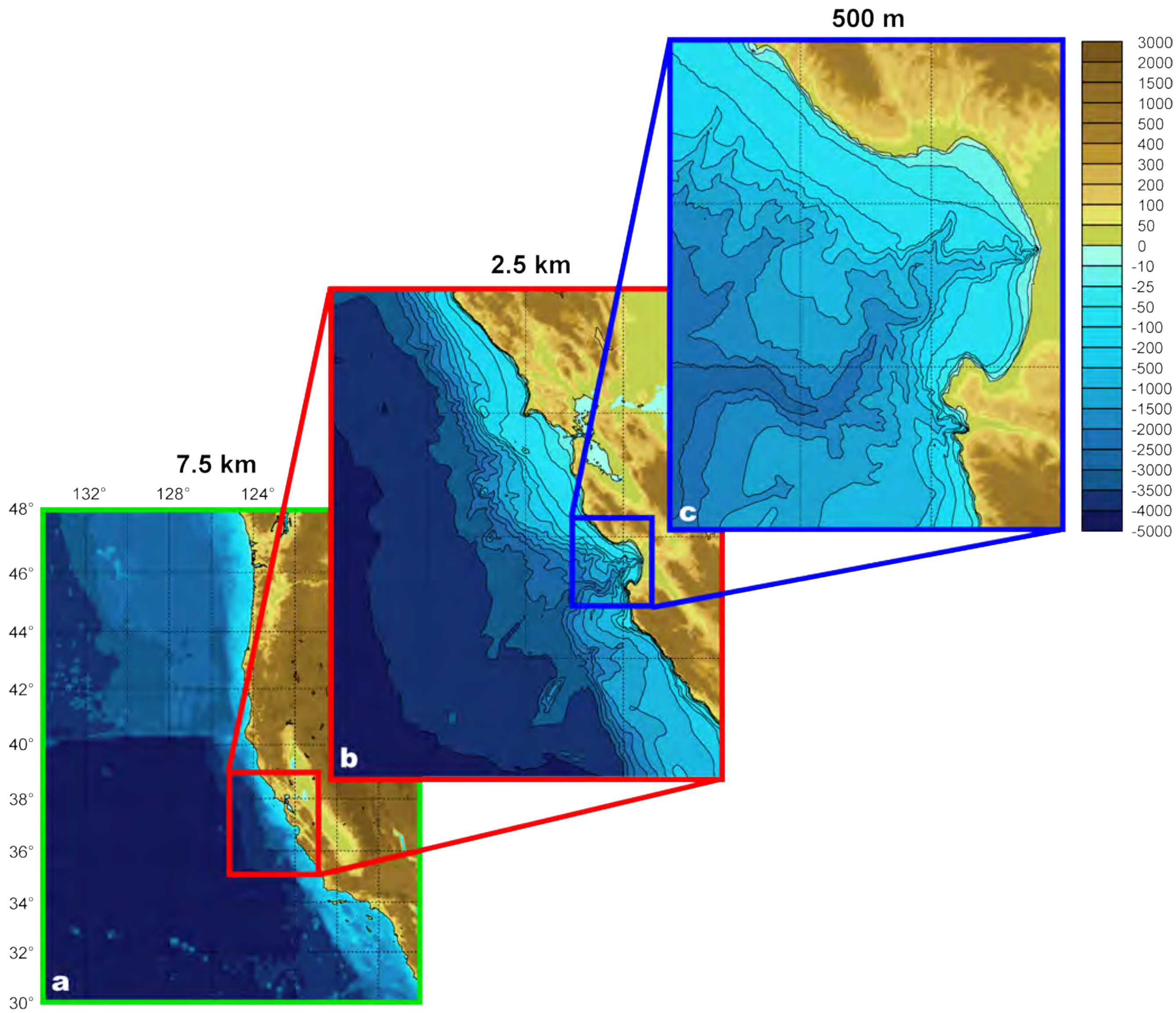

Figure 1: A ROMS nested grid approach, with increasing resolution for the California Current System. The average horizontal resolutions are: (a) 7.5km, (b) 2.5km, a nested ratio 1:3, and (c) 500m, a nested ratio 1:5. The grids mesh has been removed for clarity.

Figure 2 shows a nested application for the US east coast (grid **a**) with two imbedded *composite* grids for the Delaware Bay (grid **b**) and Chesapeake Bay (grid **c**) estuaries. In addition, it has an imbedded fine resolution *refinement* grid **d** over the Nantucket Shoals. This example shows the unique capabilities of multiple grids nesting in ROMS design. All the grids can coexist in the same application and are nested synchronously at every time step. This level of complexity in nesting design infrastructure required a careful overhaul of ROMS numerical kernels and extensive testing over the past couple of years. However, we have been maturing, testing and getting ready for this development since ROMS 3.0 was released in April of 2007. John Warner and I have been working on and off with this for several years. Indeed, to our knowledge this is one of the most complex and generic nesting approaches in an ocean model. Therefore, the implementation and porting to the community version of the code was divided in three sequential development phases:

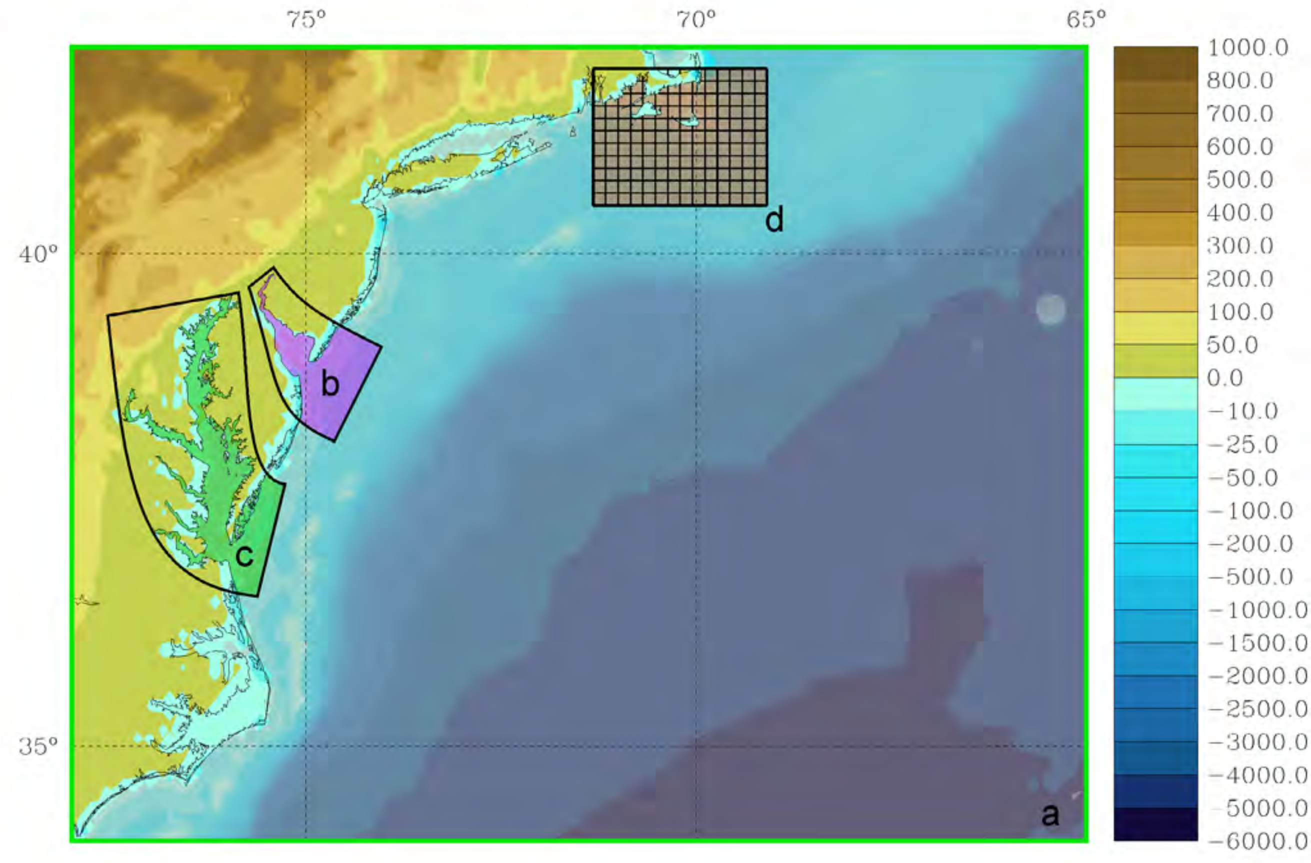

Figure 2: A US east coast example of combined composite and refinement nested-grids: (a) parent large scale, mesoscale resolution grid, (b) Delaware Bay estuary fine resolution composite grid, (c) Chesapeake Bay estuary system fine resolution composite grid, and (d) Nantucket Shoals fine resolution refinement grid. The grid meshes in (a), (b), and (c) have been removed and (d) has been substantially sampled for clarity.

- **Phase I**: the numerical kernel of ROMS nonlinear (NLM), tangent linear (TLM), representer (RPM), and adjoint (ADM) models was modified to allow different I- and J-ranges in the DO-loops to permit operations on various nested grid classes (*refinement*, *mosaic*s, and *composite*) and nesting layers (*refinement* and *composite* grid combinations). This facilitates the computation of any horizontal operator (advection, diffusion, gradient, etc.) in the nesting overlap regions and avoids the need for cumbersome lateral boundary conditions on the model variables and their associated flux/gradient values. The advantage of this approach is that it is generic to any discrete horizontal operator. Otherwise, we have to specify logic for each advection scheme available in ROMS. The overlap region is an extended section of the grid that overlays an adjacent grid. The strategy is to compute the full horizontal operator at the contact points between nested grids instead of specifying boundary conditions, as shown in Fig. 1 of Warner *et al.* (2010). The stencil footprint at the contact edge(s) of the *child* grid is expanded up to five additional computational grid-points to allow the full evaluation of the horizontal operator at its physical boundary. The values in the overlap region are determined from the *parent* grid. In *refinement* applications, the overlap values are computed by spatial averaging. This is because the *parent* grid is always larger and coarser than the *child* grid by a factor of 3, 5, or 7. In *mosaic* and *composite* grids, the overlap values are computed by interpolation from the *parent* grid. If *child* and *parent* have coincident grid points in the overlap region, the interpolation is not necessary and identical solutions are obtained when compared to that of one single large and continuous grid (Warner, *et al.*, 2010). A coincident grid point is one with the same cell size, area, orientation, bathymetry, and land/sea masking properties. In such cases, the coincident points are only needed in the overlap region.

- **Phase II**: the lateral boundary conditions C-preprocessing options were eliminated and replaced with logical switches that depend on the nested grid, if any. This facilitates, in a generic way, the processing or not of lateral boundary conditions in applications with nested grids. As mentioned above, the values at the lateral boundary points are computed directly in the overlap region by the numerical kernel. In addition, the logical switches allow different lateral boundary conditions types between active (temperature and salinity) and passive (biology, sediment, inert, etc.) tracers. The lateral boundary condition switches for each state variable and boundary edge are now specified in ROMS input script file, *ocean.in*.

- **Phase III**: the nesting calls will be added to ROMS main time-stepping routines, **main2d** and **main3d**. The routine **main2d** is only used in shallow-water 2D barotropic applications whereas **main3d** is used in full 3D baroclinic applications. These main time-stepping routines, in turn, call several routines of the ROMS kernel to sub-time step (predictor and corrector) each term in the governing equations sequentially: right-hand-side terms, turbulent mixing, 2D momentum, 3D momentum, continuity equation, and tracers. In **Phase III**, several routines will be added to process the information that it is required in the overlap region, what information needs to be exchanged from/to another grid, and when to exchange it. In grid *refinement* applications, the information is exchanged at the end of the full time-step (bottom of **main2d** or **main3d**). Contrarily, in *mosaic* and *composite* grid applications, the information is exchanged between each sub-time step call in **main2d** or **main3d**. That is, the *parent* and the *mosaic*/*composite* grids need to sub-time step the 2D momentum equations before any of them start solving and coupling the 3D momentum equations. Therefore, the governing equations are solved and nested in a synchronous fashion. The concept of nesting layers is introduced to allow applications with both *composite* grids and *refinement* grids, as shown in Fig. 2. Here, two nesting layers are required. In the first nesting layer, the *parent* grid (**a**) and *composite* grids (**b** and **c**) are synchronously sub-time stepped for each governing equation term. Then, in the second and last nesting layer, the *refinement* grid (**d)** is time stepped and the information between *parent* (**a**) and *refinement* (**d**) grids are exchanged at the end of the time step. The exchange between grids can be one-way or two-way.

The changes made to the code during **Phases I** and **II** were significant and required several months of coding and over a year to extensively test all the nonlinear and adjoint-based algorithms. All the idealized and realistic test cases distributed with ROMS were updated and tested to guarantee identical solutions with previous versions of ROMS in both serial and parallel (MPI and OpenMP) computations. **Phase I** was released to the community as ROMS **3.5** on April 25, 2011. **Phase II** was released as ROMS **3.6** on September 23, 2011. The final **Phase III** will be released as ROMS **4.0** in the near future, hopefully sometime in January 2012.

A Graphical User Interface (GUI) is currently under development to help prepare the ROMS standard input file, *ocean.in*. The added complexity in ROMS nested grids makes this input file very confusing and difficult to edit by hand. A sample of the ROMS GUI is shown in Fig. 3. The GUI is written in Python to facilitate cross platform capabilities, ease of maintenance, and code readability. This GUI will be released to the community in the near future.

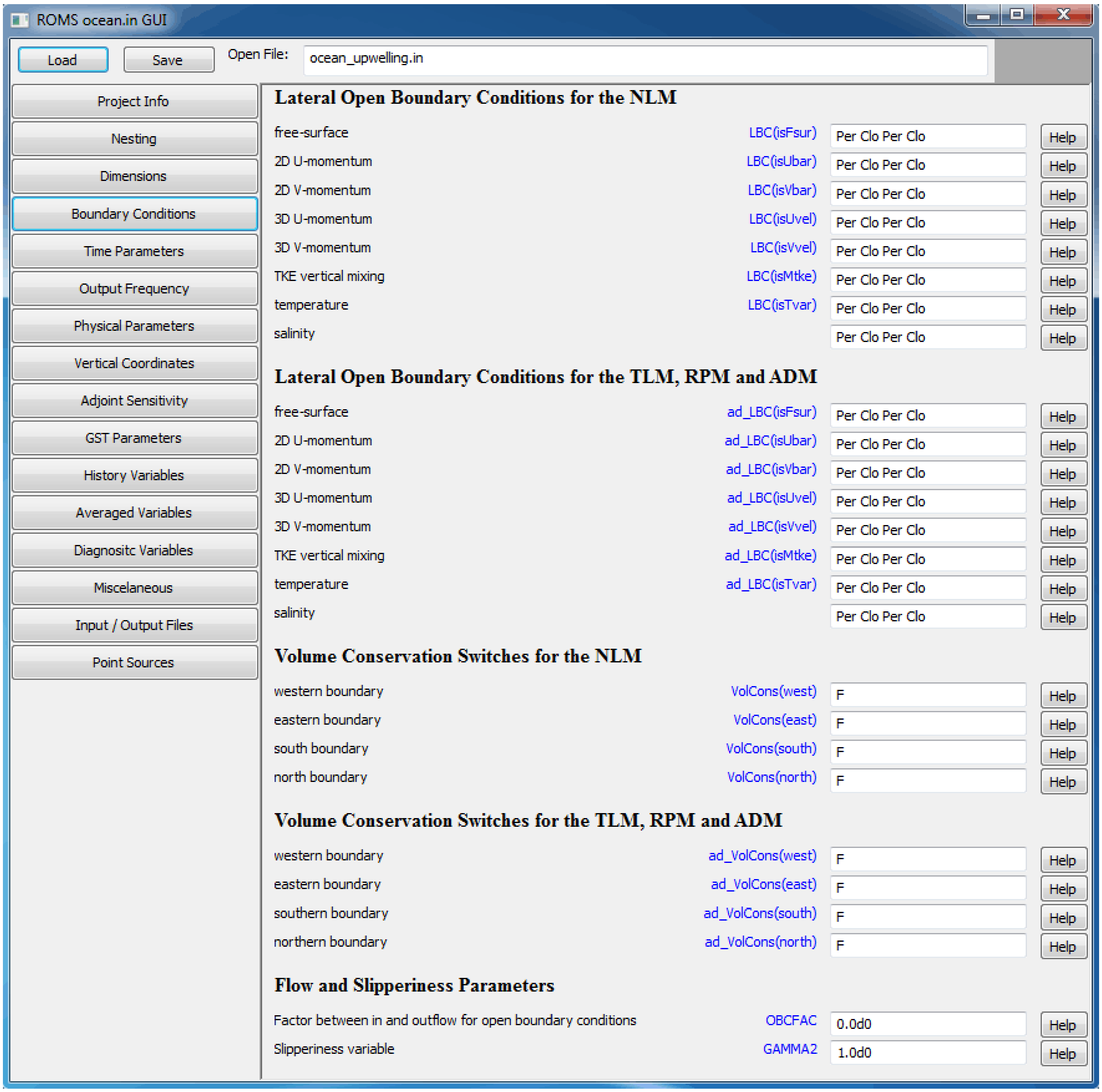

Figure 3: ROMS standard input file python-based Graphical User Interface (GUI).

IMPACT/APPLICATIONS

This project will provide the ocean modeling community with a freely accessible, well documented, open-source, terrain-following, ocean model for regional nowcasting and forecasting that includes advanced data assimilation, ensemble prediction, and analysis tools for adaptive sampling and circulation dynamics, stability, and sensitivity.

TRANSITIONS

The full transition of ROMS/TOMS to the operational community is likely to occur in the future. However, the ROMS/TOMS algorithms are now available to the developers and scientific and operational communities through the website http://www.myroms.org/.

RELATED PROJECTS

The work reported here is related to other already funded ONR projects using ROMS. In particular, the PI (H. Arango) closely collaborates with A. Moore (adjoint-based algorithms) at University of California, Santa Cruz, A. Miller and B. Cornuelle (ROMS adjoint and variational data assimilation) at Scripps Institute of Oceanography, E. Di Lorenzo (Southern California predictability) at Georgia Institute of Oceanography, and J. Wilkin (Mid-Atlantic Bight variational data assimilation) at Rutgers University.

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