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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http://www.ocean-modeling.org

LONG-TERM GOALS

The long-term technical goal is to design, develop and test the next generation primitive equation, Terrain-following Ocean Modeling System (TOMS) for high-resolution scientific and operational 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 Terrain-following Ocean Modeling System 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), like 4-Dimensional Variational (4DVar) data assimilation, ensemble prediction, adaptive sampling, and circulation stability and sensitivity analysis.

APPROACH

The framework for 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; Shchepetkin and McWilliams, 2005). The governing dynamical equations are discretized on a vertical coordinate that depend 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),

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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). 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 perturbing 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. There are several adjoint-based variational data assimilation algorithms available in ROMS. For cases in which the dynamics are imposed as a strong constraint (*i.e*. no model error assumed), there is an incremental 4DVar (Powell et al., 2007a, b) driver (IS4DVAR) similar to that used operationally at some numerical weather prediction centers. In the case where errors are admitted in the model, there is an indirect representer-based weak constraint 4DVar (Di Lorenzo et al., 2007; Muccino et al., 2007) driver (W4DVAR) and a weak constraint Physical Space Analysis System (W4DPSAS) driver. 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. There are three types of nesting capabilities in ROMS: (i) *refinement* grids which provide increased resolution (3:1 or 5:1) 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.

WORK COMPLETED

The ROMS/TOMS various algorithms have been used successfully in several real-time observational and prediction experiments:

The ROMS/TOMS incremental, strong constraint 4DVar algorithms were used for real-time prediction during the Shallow Water Acoustics Experiment (SW06) over the Mid-Atlantic Bight shelf break in the summer of 2006. A 5-km resolution regional model of the study area was used to assimilate data gathered from various sources including glider observations, shipboard CTDs and XBTs, scanfish profiles, underway thermosalinograph data, CODAR and shipborne ADCP currents, daily composite SST, and gridded altimetry SSH anomalies (AVISO). The data was assimilated sequentially over 2-day interval cycles to estimate the initial conditions for the next daily forecast (http://myroms.org/sw06). This was big effort involving several scientists, students and data support personnel. One of our major achievements was to create all the software needed to ingest such diverse data streams into ROMS.

The strong constraint 4DVar and ensemble prediction algorithms are currently running in real-time onboard the RCCL vessel *Explorer of the Seas* to forecast upper-ocean conditions in the Intra-Americas Sea (IAS) which includes the Caribbean Sea and Gulf of Mexico. The system is fully automated now and has been running continuously since January 7, 2007 (Powell, *et al*., 2007a, b). It assimilates satellite SST, SSH, and shipborne ADCP currents. The initial conditions generated from data assimilation are perturbed to generate around 50 ensembles per week. Forecasts are updated daily at http://www.myroms.org/ias. During the first six weeks, project personnel were onboard to perform experiments, monitor the forecast system, and participate in public education and outreach activities like lectures and tours of the laboratory facilities.

Several real-time forecasts in the Philippine Archipelago were carried out from May 17 to June 23, 2007. This is part of an ONR-supported direct research initiative to study the meso- and submesoscale dynamics in Straits of the Philippine Archipelago (denoted as PhilEx). The daily forecasts, without data assimilation, provided support for the PhilEx exploratory cruise and can be found at http://www.myroms.org/philex . Each prediction cycle, updated daily, was run for 9 days (4-day hindcast and 5-day forecast). The model was initialized 4 days prior to the forecast cycle starting day to use reanalyzed atmospheric and boundary forcing. The atmospheric forcing used was from NOGAPS 3-hours, half-degree resolution. The lateral boundary conditions were from HyCOM 1/12 degree global run with NCODA. The tidal forcing was from the global OTPS model.

RESULTS

After several years of development, ROMS/TOMS version 3.0 was released to the entire user community on April 27, 2007. This version includes several adjoint-based algorithms which can be used to enhance ocean prediction and analysis. ROMS/TOMS is now an open-source code and distributed, using Subversion (svn) revision control software, to the ocean modeling community under similar conditions to the MIT/X License (http://myroms.org/license). As far as we know, ROMS/TOMS is one of the first truly community Numerical Ocean Prediction (NOP) systems freely distributed to hundreds of users worldwide.

A new code managing website, based on Trac, was developed to maintain the official versions of ROMS/TOMS. It can be used for version and bug tracking, code browsing, and development timelines and roadmaps (Figure 1). This web site provides an interface to Subversion and a Wiki providing detailed documentation to code downloads, algorithm updates, bug reports (Tickets) and fixes, and new code developments. The link for this web site is https://www.myroms.org/projects/src. It is password protected so only registered users have access to the source code. The registration is free and access is authorized to every user that fills the registration form. Currently, there are over 1150 registered users from all over the world. Other Trac-based websites were also developed to maintain private branches of ROMS/TOMS to help the testing and exchange of new algorithms between developers. Access to these braches is limited to few advanced users and developers.

The web-based documentation (Figure 2) of ROMS/TOMS is in the early stages and located at https://www.myroms.org/wiki. This complex web site, named WikiROMS, provides different levels of

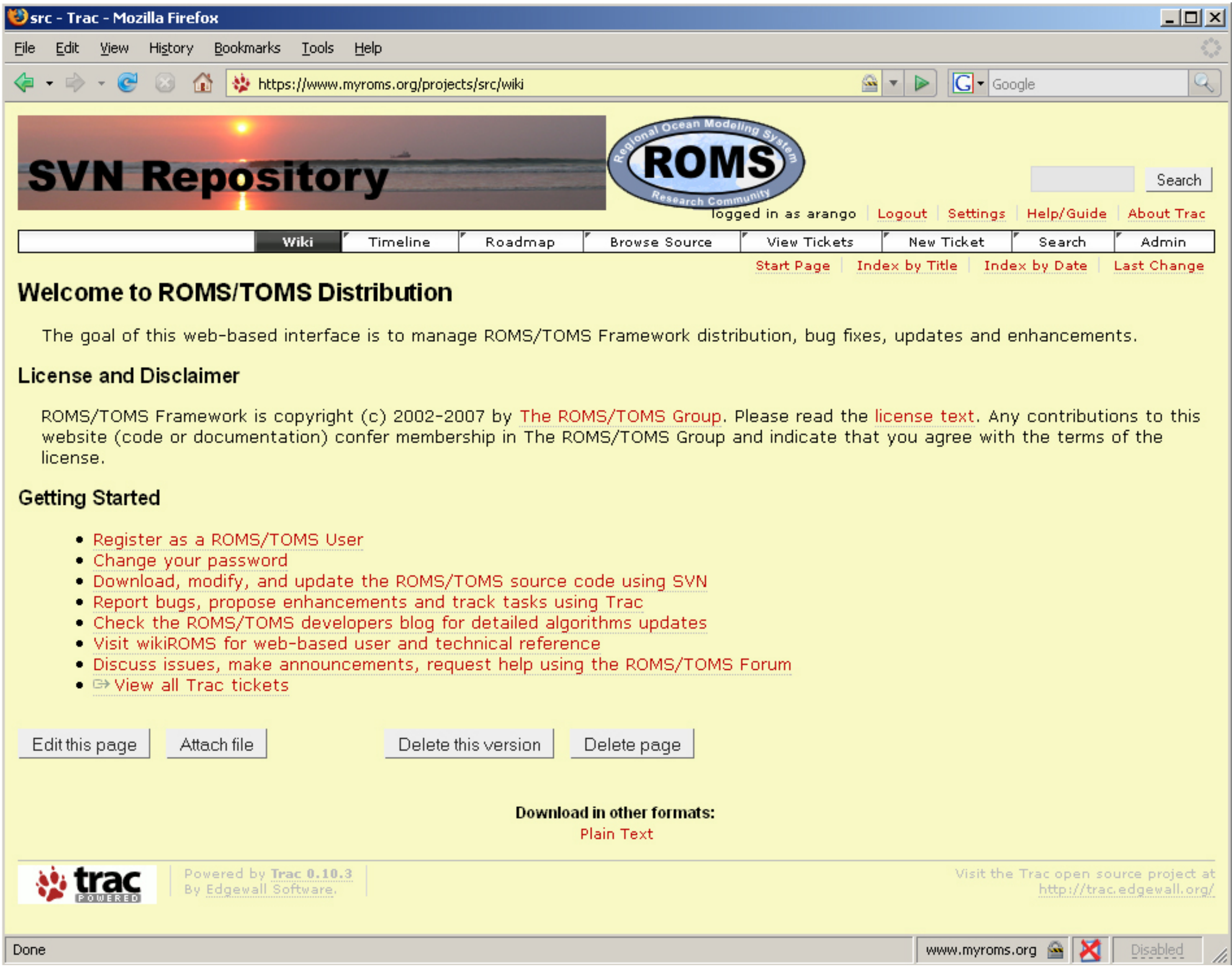

Figure 1: A screenshot of ROMS svn repository website https://www.myroms.org/projects/src using the Trac wiki interface and issue tracking system for software development

documentation for novice and advanced users. We expect the user community to participate actively in its development.

The next ROMS/TOMS user's workshop will be held at University of California, Los Angeles Oct 1-5, 2007. The formal workshop presentations are scheduled for October 1st and 2nd, followed by a training session on October 3rd. This will be followed by the CSTM meeting October 4th and 5th.

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.

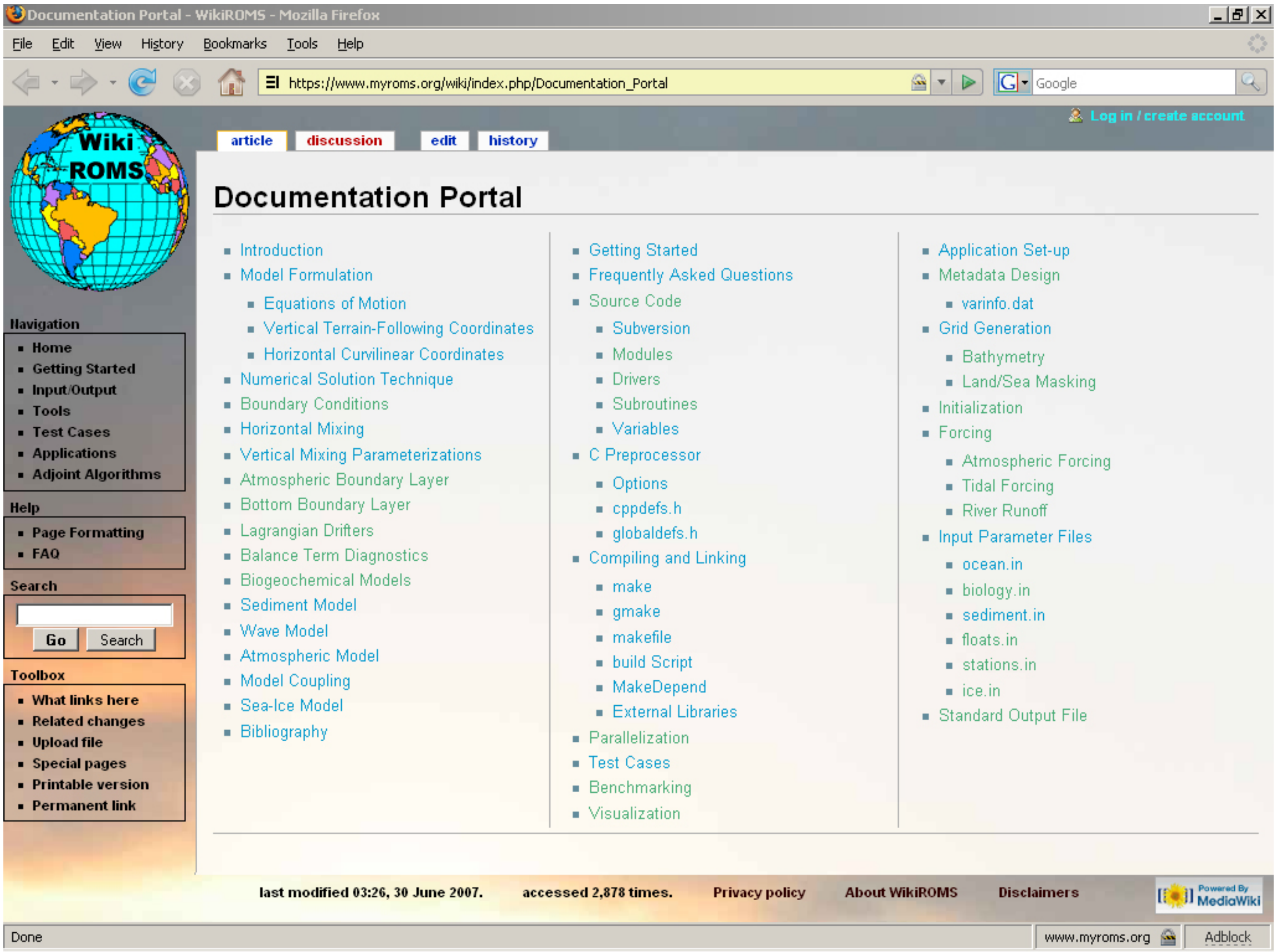

Figure 2: WikiROMS website portal https://www.myroms.org/wiki for technical, numerical, usage, and model configuration documentation.

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 https://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 and B. Powell (Intra-Americas Sea trials, http://www.myroms.org/ias) 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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