

A Community Terrain-Following Ocean Modeling System

Tal Ezer

Program in Atmospheric and Oceanic Sciences

P.O. Box CN710, Sayre Hall

Princeton University

Princeton, NJ 08544-0710

phone: (609) 258-1318 fax: (609) 258-2850 email: ezer@splash.princeton.edu

Grant #: N000140010228

<http://www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/>

LONG-TERM GOALS

The long-term goals of this effort are to: 1) develop and evaluate an expert Terrain-following Ocean Modeling System (TOMS) that will provide a state of the art model and supporting tools for simulations of a wide range of problems and scales; 2) support the Navy's efforts in improving operational coastal ocean forecasting systems; and 3) provide continuous support for the terrain-following ocean modeling community and provide coordination channels between developers, user and forecasters.

OBJECTIVES

The main objective is to develop a robust modeling system with various options for relocatable coastal forecasting systems for the Navy and for other problems ranging from coastal to global ocean circulation. Such a system should include accurate and efficient numerical algorithms, the latest suite of vertical mixing schemes, interfaces for coupling with atmospheric models, nesting capability, various data assimilation schemes, and a parallel framework for both shared-memory (OpenMP) and distributed-memory (MPI) paradigms. The system should also include web-based documentation and user-support software for model set-up, analysis and diagnostics.

APPROACH

Developing and supporting community ocean models requires a collaborative effort by ocean model developers and the terrain-following ocean modeling community. This effort is thus based on a joint collaboration between the two most widely used terrain-following community ocean modeling groups, at Princeton University (T. Ezer, PI) and at Rutgers University (H. Arango, PI). The two PIs, who manage the respective community models (POM, Blumberg and Mellor, 1987; ROMS/TOMS, Haidvogel et al., 2000; Shchepetkin and McWilliams, 2003; Ezer et al., 2002), play an important ambassador role by communicating and coordinating with developers at several other institutions (UCLA, MIT, University of Colorado and others) and with users. We also organize biennial users' workshops, as well as developers meetings. The approach of testing new schemes includes intercomparisons of various schemes (e.g., turbulence mixing options) and sensitivity studies with idealized and realistic cases. Important testing of new model elements is done by beta testers who provide feedback to the developers.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 30 SEP 2003		2. REPORT TYPE		3. DATES COVERED 00-00-2003 to 00-00-2003	
4. TITLE AND SUBTITLE A Community Terrain-Following Ocean Modeling System				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Program in Atmospheric and Oceanic Sciences,,P.O. Box CN710, Sayre Hall,Princeton University,,Princeton,,NJ, 08544				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT The long-term goals of this effort are to: 1) develop and evaluate an expert Terrain-following Ocean Modeling System (TOMS) that will provide a state of the art model and supporting tools for simulations of a wide range of problems and scales; 2) support the Navy's efforts in improving operational coastal ocean forecasting systems; and 3) provide continuous support for the terrain-following ocean modeling community and provide coordination channels between developers, user and forecasters.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Same as Report (SAR)	18. NUMBER OF PAGES 8	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

WORK COMPLETED

Several new numerical features developed during the past couple of years have been included in the latest version of the code known as TOMS/ROMS 2.0; this code was distributed to about fifty beta testers in January, 2003, and made publically available to the community in June, 2003.

The code includes various pressure gradient algorithms (Ezer et al., 2002; Shchepetkin and McWilliams, 2003) that are more accurate and efficient than previous schemes used in SPEM, SCRUM and POM (Beckman and Haidvogel, 1993; Chu and Fan, 1997; Song, 1998; Mellor et al., 1994, 1998). Several advection algorithms are available with second-, third- and fourth-order accuracy, and a predictor-corrector time stepping scheme may allow the use of a longer time step than standard schemes do (for details, see an evaluation and comparison of these algorithms in Ezer et al., 2002). In collaboration with Warner and Sherwood (USGS), a sediment model and generic length scale (GLS) turbulence parameterization (Umlauf and Burchard, 2003) have been added to the code; this adds more options to the original Mellor-Yamada level 2.5 turbulent closure scheme (Mellor and Yamada, 1982) and the KKP mixing scheme (Large et al., 1994). A recent study (Warner et al., 2003) evaluated the performance of these turbulence closures in terms of idealized sediment transport applications. Various data assimilation schemes, including tangent linear, adjoint, variational data assimilation and ensemble forecasting have been developed and are being tested through collaboration with scientists from the University of Colorado (Moore) and Scripps (Miller and Cornuelle), see Moore et al., (2003) and Arango et al. (2003) for details.

Particular model development work at Princeton (in collaboration with G. Mellor and others) includes the testing of a generalized coordinate system (Mellor et al., 2002) that allows to compare mixing processes in z-level grid with sigma coordinate or generalized terrain-following grids, using otherwise identical numerics (Ezer and Mellor, 2003). This work may support the future development of a hybrid, or a general coordinate version of TOMS. Other work at Princeton in recent years focused on improving turbulence mixing schemes by including: 1. better parameterizations of dissipation due to internal waves (Ezer, 2000; Mellor, 2001), and 2. current-wave interaction and breaking waves energy contribution to both the bottom and the surface mixed layers (Mellor, 2002, 2003; Mellor and Blumberg, 2003).

As part of the PIs role in coordinating the efforts of model developers and in providing a forum for exchange of ideas and research within the ocean modeling community, two workshops were organized during FY03. The second TOMS developers workshop was held in Boulder, CO, July 10-11, 2003, with participation of most model development teams involved and ONR personnel. The third biennial, terrain-following users workshop was held in Seattle, WA, August 4-6, 2003. The meeting focused on several important modeling issues such as mixing parameterizations, data assimilation and new developments in numerical techniques (the meeting's proceedings, Ezer et al., 2003, is available from the ROMS or POM web pages). During the last two years both groups completed the first stage in improving the web-based information for their respective community models (www.aos.princeton.edu/WWWPUBLIC/htdocs.pom; marine.rutgers.edu/po), both, in terms of look and services provided. Due to the collaboration between the two groups, there are now more common diagnostics and grid generation tools (matlab and netcdf based) that are being used by users of different models. A new generic ocean modeling web page (www.ocean-modeling.org) is partly completed; it will serve the needs of modelers of both groups as well as the ocean modeling community at large.

RESULTS

The modular TOMS coded has been converted to F90/F95, with a parallel framework that allows both shared- (OpenMP) and distributed-memory (MPI) paradigms. Benchmark tests are underway to evaluate code performance on different computer architectures. For example, an idealized upwelling test with small (128x128x16) and larger (256x256x16) grid resolutions is used to evaluate and compare OpenMP versus MPI on the NOAA/GFDL Origin 3800 supercomputer cluster (Figure 1). The MPI code improves its efficiency (up to 32 nodes) in the larger grid, but its performance is degraded due to the increased communications cost over 48 nodes. On the other hand, the OpenMP code exhibits super-linear performance up to 64 processors in the larger grid (Figure 1a). Time profiling over all processors reveals that, as the number of processor increases, the MPI code spends considerable more time than the OpenMP code on output (Figure 1b). Serial I/O (NetCDF) is much cheaper in shared-memory configurations. We are currently working on a parallel I/O option for TOMS based on HDF. Unidata is now working on a parallel version of the NetCDF library, which will be available sometime next year.

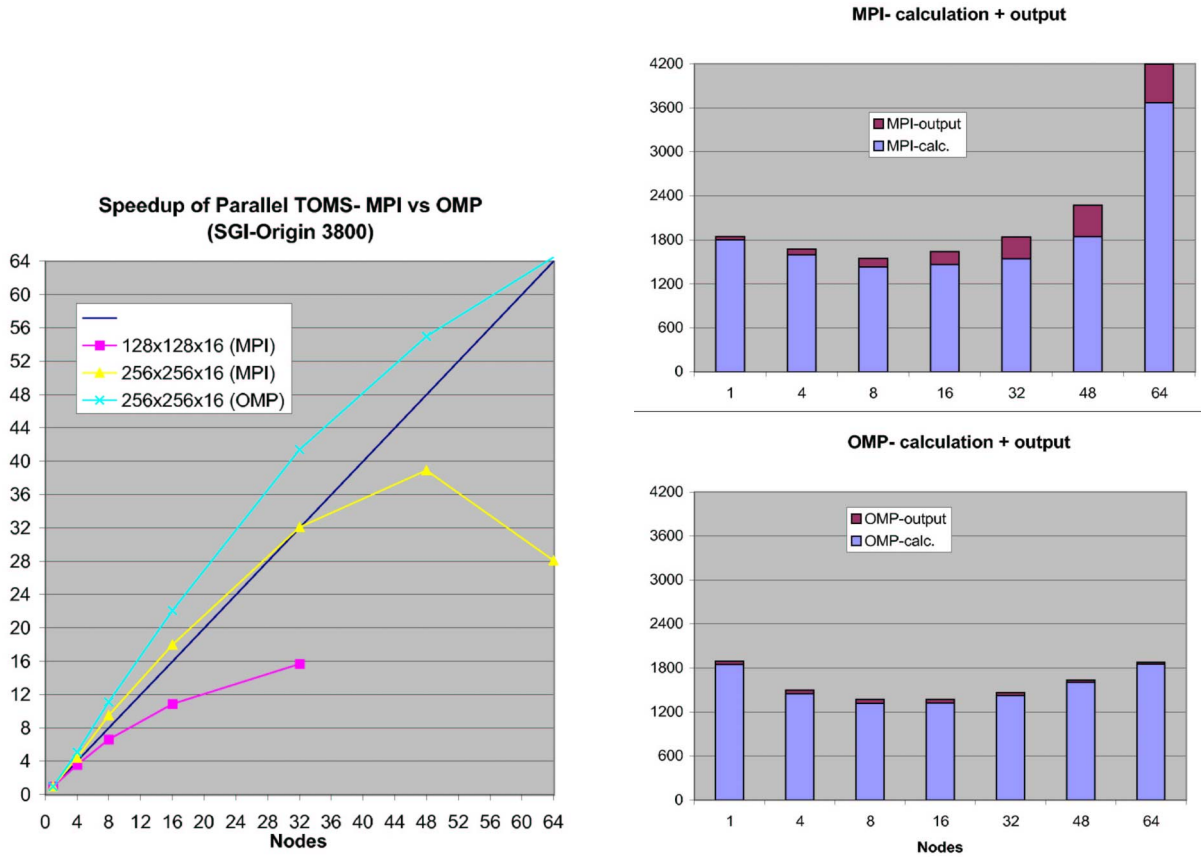


Figure 1a (left). The speedup factor of TOMS code as a function of the number of processors used. Purple and yellow lines represent small and large domains, respectively, using the MPI code; the cyan line represents large domain using the OpenMP code, which shows super linear behavior up to 64 processors. **Figure 1b (right).** The total cpu (sec) summed over all processors for the large domain MPI (top) and OpenMP (bottom) codes. The dark portion of each bar represents the relative portion of the calculations spent on writing output, which takes considerably more calculations in the MPI code as the number of processors increases.

During the past year, several projects at Princeton (some supported by other grants) contributed to the general model development efforts. Studies of mixing processes in the bottom boundary layers (BBL) and turbulence parameterizations used the generalized coordinate system as implemented by Mellor et al. (2002), to compare various grid classes. In particular, simulations of overflow transports and entrainment demonstrate that a relatively coarse resolution terrain-following grid performs as well as much higher resolution z-level grid when all other numerical aspects are identical (Ezer and Mellor, 2003). The study also indicates the difficulty that general coordinate or hybrid models may face in implementing horizontal and vertical mixing parameterizations. For example, increasing horizontal diffusion resulted in thinner BBL in the terrain-following grid, but caused a thicker BBL in the z-level grid. These studies may help in future developments of hybrid or generalized coordinate systems to be evolved from a basic terrain-following model (in contrast to hybrid models build from isopycnal models, such as HYCOM).

In recent years, attempts are being made to couple ocean circulation models with wave models. However, how to include the surface waves motion and breaking waves in the parameterization of oceanic mixing is still a new field of research (Mellor, 2002, 2003; Mellor and Blumberg, 2003). These studies (as well as other research efforts to develop a theory for wave-current interactions by McWilliams and others) give a new framework for improving turbulence mixing in ocean models; this efforts may be important in particular for coastal forecasting systems over shallow regions. Preliminary results (see above papers as well as the special session on this issue in the 2003 users meeting, Ezer et al., 2003) indicate the potential of improving simulations of surface currents, surface mixed layers and oceanic thermal structures.

IMPACT/APPLICATIONS

Improved numerical schemes and new features for terrain-following ocean models is having an immediate impact on the many users of this class of models (over 2000 users are now registered in the POM and TOMS/ROMS user groups). In particular, many users in the Navy's labs and operational centers presently use one of these models.

TRANSITIONS

An official transition of the latest TOMS to an operational Navy's code has not been done yet, but operational centers at NOAA and Navy labs has been using either POM or ROMS being used for research and forecasting purposes. These experiences and the interaction of the PIs with the operational centers will benefit future transitions.

RELATED PROJECTS

Under separate funding, the Princeton group is involved in the development and testing of forecasting systems for the western North Atlantic and the Gulf of Mexico (see the Princeton Regional Ocean Forecast System, PROFS, www.aos.princeton.edu/WWWPUBLIC/PROFS/). Studies of wave-induced turbulence by G. Mellor may help to improve future mixing schemes in TOMS. Our involvement in the project, the Dynamics of Overflow Mixing and Entrainment (DOME, www.rsmas.miami.edu/personal/tamay/DOME/dome.html), which recently became part of the gravity current entrainment Climate Process Team (CPT), will help to evaluate important test cases, improve mixing parameterizations, and compare results with other models. There is also ongoing collaboration

at Princeton University with model development efforts at the Geophysical Fluid Dynamics Laboratory (NOAA/GFDL).

REFERENCES

- Beckmann, A. and D. Haidvogel, 1993: Numerical simulation of flow around a tall isolated seamount, *J. Phys. Oceanogr.*, 23, 1736-1753.
- Blumberg, A. F., and G. L. Mellor, 1987: A description of a three-dimensional coastal ocean circulation model. *Three-Dimensional Coastal ocean Models*, edited by N. Heaps, American Geophysical Union, 1-16.
- Chu, P. C. and C. Fan, 1997: Sixth-order difference scheme for sigma coordinate ocean models, *J. Phys. Oceanogr.*, 27, 2064-2071.
- Ezer, T., H. Arango and A. Hermann (Eds.), 2003: *2003 Terrain-following Ocean Models Users Workshop*, Proc., 4-6 August, Seattle, Wa, Princeton University, 19 pp.
- Ezer, T., 2000: On the seasonal mixed-layer simulated by a basin-scale ocean model and the Mellor-Yamada turbulence scheme. *J. Geophys. Res.*, 105, 16,843-16,855.
- Ezer, T., H. Arango and A. Shchepetkin, 2002: Developments in terrain-following ocean models: Intercomparisons of numerical aspects, *Ocean Modelling*, 4, 249-267.
- Ezer, T. and G. L. Mellor, 2003: A generalized coordinate ocean model and a comparison of the bottom boundary layer dynamics in terrain-following and in z-level grids, *Ocean Modelling*, In Press.
- Haidvogel, D.B., H.G. Arango, K. Hedstrom, A. Beckmann, P. Malanotte-Rizzoli, and A.F. Shchepetkin, 2000: Model evaluation experiments in the North Atlantic Basin: Simulations in nonlinear terrain-following coordinates, *Dyn. Atmos. Ocean*, 32, 239-281.
- Large, W. G., J. C. McWilliams, and S. C. Doney, 1994: A Review and model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, 32, 363-403.
- Mellor, G. L., 2001: One dimensional, ocean surface layer modeling, a problem and a solution. *J. Phys. Oceanogr.*, 31, 790-809.
- Mellor, G. L., 2002: Oscillatory bottom boundary layers. *J. Phys. Oceanogr.*, 32, 3075-3088.
- Mellor, G. L., 2003: The three-dimensional current and wave equations. *J. Phys. Oceanogr.*, 33, 1978-1989.
- Mellor, G. L. and A. F. Blumberg, 2003: Wave breaking and ocean surface layer thermal response. Submitted.
- Mellor, G.L., T. Ezer and L.-Y. Oey, 1994: The pressure gradient conundrum of sigma coordinate ocean models, *J. Atmos. Ocean. Tech.*, 11, Part 2, 1126-1134.

Mellor, G. L., L.-Y. Oey and T. Ezer, 1998: Sigma coordinate pressure gradient errors and the seamount problem, *J. Atmos. Ocean Tech.*, 15(5), 1122-1131.

Mellor, G. L. and T. Yamada, 1982: Development of turbulent closure model for geophysical fluid problems. *Rev. Geophys.*, **20**, 851-875.

Mellor, G. L., S. Hakkinen and T. Ezer and R. Patchen, 2002: A generalization of a sigma coordinate ocean model and an intercomparison of model vertical grids, In: *Ocean Forecasting: Conceptual Basis and Applications*, N. Pinardi and J. D. Woods (Eds.), Springer, 55-72.

Moore, A.M, H.G. Arango, E. Di Lorenzo, B.D. Cornuelle, A.J. Miller, and D.J. Neilson, 2003: A Comprehensive Ocean Prediction and Analysis System based on the Tangent linear and Adjoint of a Regional Ocean Model, *Ocean Modelling*, Submitted.

Shchepetkin, A. F. and J. McWilliams, 2003: A methods for computing horizontal pressure gradient force in an oceanic model with non-aligned vertical coordinate. *J. Geophys. Res.*, 108(C3), 10.1029/2001JC001047.

Song, Y. T., 1998: A general pressure gradient formulation for ocean models. Part I: Scheme design and diagnostic analysis, *Mon. Weath. Rev.*, 126, 3213-3230.

Umlauf, L., and Burchard, H., 2003: A generic length-scale equation for geophysical turbulence models. *J. Mar. Res.*, in press.

Warner, J.C., C.R. Sherwood, H.G. Arango, B. Butman, R.P. Signell, 2003: Performance of four turbulence closure methods implemented using a generic length scale method. *Ocean Modelling*, Submitted.

PUBLICATIONS

Dong, C., R. Houghton, H.-W. Ou, D. Chen and T. Ezer, 2003: Numerical study of the diapycnal flow through a tidal front with passive tracers, *J. Geophys. Res.*, [submitted, refereed].

Ezer, T., H. Arango and A. Shchepetkin, 2002: Developments in terrain-following ocean models: intercomparisons of numerical aspects, *Ocean Modelling*, 4, 249-267 [published, refereed].

Ezer, T., H. Arango and A. Hermann (Eds.), 2003: *2003 Terrain-following Ocean Models Users Workshop*, Proceedings, Princeton University, 19 pp [published].

Ezer, T. and G. L. Mellor, 2003: A generalized coordinate ocean model and a comparison of the bottom boundary layer dynamics in terrain-following and in z-level grids, *Ocean Modelling*, [in press, refereed].

Ezer, T., L.-Y. Oey and H.-C. Lee, 2002: Simulation of velocities in the Yucatan Channel, In: *Proc. Oceans 2002, MST/IEEE*, 1467-1471 [published].

Ezer, T., L.-Y. Oey, H.-C. Lee and W. Sturges, 2003: The variability of currents in the Yucatan Channel: Analysis of results from a numerical ocean model, *J. Geophys. Res.*, 10.1029/2002JC001509 [published, refereed].

Mellor, G. L., S. Hakkinen and T. Ezer and R. Patchen, 2002: A generalization of a sigma coordinate ocean model and an intercomparison of model vertical grids, In: *Ocean Forecasting: Conceptual Basis and Applications*, N. Pinardi and J. D. Woods (Eds.), Springer, 55-72 [published, refereed].

Wang, D.-P., L.-Y. Oey, T. Ezer and P. Hamilton, 2003: Nearsurface currents in DeSoto Canyon (1997-1999): Comparison of current meters, satellite observation, and model simulation, *J. Phys. Oceanogr.*, 33, 313-326 [published, refereed].