

# **A Community Terrain-Following Ocean Modeling System**

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## **LONG-TERM GOALS**

This project is part of a new collaborative effort aimed at the long term goal of providing improved terrain-following ocean models for the U.S. Navy's operational purposes, as well as for the general use of the ocean modeling community. An expert Terrain-following Ocean Modeling System (TOMS) that includes the most advanced numerical algorithms, data assimilation, air-sea coupling, as well as supporting diagnostic and analysis tools will be built, evaluated and tested for this purpose. The development of new numerical algorithms, such as new pressure gradient schemes, may also have long-term impact on the sigma coordinate modeling community at large.

## **OBJECTIVES**

The main objective is to develop an expert Terrain-following Ocean Modeling System that will be useful for a wide range of scales, applications and users' experience levels. Therefore, research is needed to test and select the most robust and efficient algorithms for the system. Different sub grid-scale parameterizations and numerical options need to be tested, as well as other options such as nesting, advanced data assimilation schemes, and coupling with atmospheric forecasting models. Considerable efforts are especially needed in upcoming years in testing general coordinate systems that may combine features of z-level, sigma and isopycnal coordinates. Development of a user friendly web-based documentation and users-support software, is an objective that is essential for efficient communications between developers, operational forecasters and users.

## **APPROACH**

This project is a joint effort of Princeton University (T. Ezer, PI) and Rutgers University (H. Arango, PI), with a close collaboration with developers at UCLA (A. Shchepetkin). Arango and Ezer currently support the two community ocean models, the Princeton Ocean Model, POM (Blumberg and Mellor, 1987), and the Regional Ocean Model System, ROMS (Haidvogel et al., 2000), and are part of the core development and testing team of TOMS. They also serve as coordinators between other modeling groups and the ocean modeling community. The approach taken in the development process involves testing of new model elements as they are being developed and immediately providing test results and new algorithms to users for further tests in other applications. Model intercomparison studies will test different numerical elements and different model parameters in order to help choose the best features for the future modeling system.

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## WORK COMPLETED

Developing a new expert modeling system is an ambitious long-term project. However, much has been achieved so far in terms of coordinating the efforts of several development groups and starting the testing of several new numerical elements. A prototype of TOMS is currently being build based on ROMS design and numerical algorithm kernel, but in Fortran 90 instead of Fortran 77. In collaboration with other data assimilation groups, basic and advanced data assimilation schemes, such as nudging, optimal interpolation, tangent linear, adjoint, 4DVAR and ESSE are being added to the system. In particular, progress has been made in the construction of the tangent linear and adjoint codes for the model. At Princeton, work on improving surface layer modeling in the Mellor and Yamada (1982) turbulence scheme has been completed and tested in one-dimensional (Mellor, 2001) and three-dimensional (Ezer, 2000) models. A generalized version of POM has been constructed (Mellor et al., 2001).

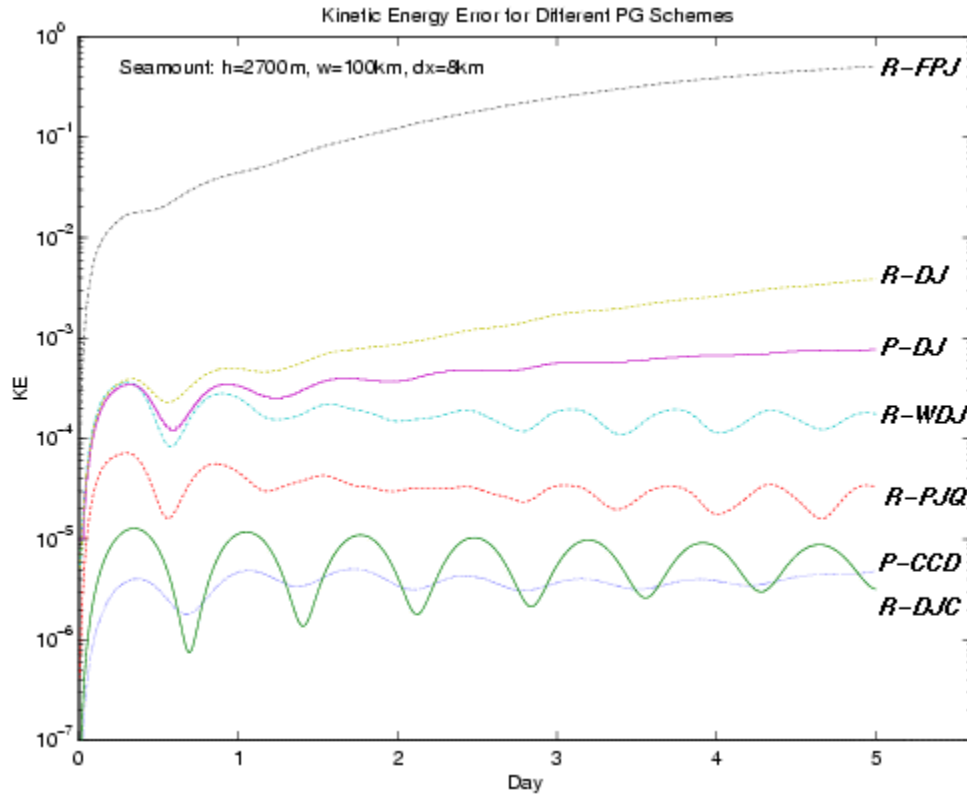
Playing the role of ambassadors and coordinators for this project, the PIs met with Navy's personnel and modelers in order to better understand the Navy's modeling efforts and needs and discuss the TOMS concept. Initial coordination with the MICOM/HYCOM ocean modeling community has been established, which will be beneficial for future development of a generalized coordinate system for TOMS. The PIs also recently organized the second joint biannual Terrain-following ocean modeling workshop in Boulder, August 20-22 (Arango and Ezer, 2001), and the TOMS inaugural meeting in Boulder, August 23. During the TOMS meeting, leading experts in ocean modeling discussed issues relating to ocean modeling in general and the development of TOMS in particular. Summaries from this meeting will help to direct future planning for this project.

## RESULTS

Research at Princeton during FY01 involved evaluation and testing of different numerical algorithms through comparisons between ROMS and POM. In particular, advection schemes, time stepping algorithms and pressure gradient schemes have been tested using an idealized steep seamount test problem. Schemes were tested for their numerical errors, computational cost and numerical stability.

While POM uses relatively standard numerics such as a Leap-Frog (LF) time stepping, ROMS (and TOMS) uses more sophisticated numerical schemes, with a two-step Predictor-Corrector (PC) time stepping, and a more complex coupling scheme between the baroclinic and barotropic modes (Shchepetkin and McWilliams, 2000). Sensitivity experiments over large range of baroclinic and barotropic time steps reveals considerable differences in the numerical stability and behavior of the two models. While choosing a time step in POM is simple, and is determined by the barotropic wave propagation speed (the CFL condition), in ROMS the choice is more difficult, since the model stability more strongly depends on both the baroclinic and barotropic time steps and the ratio between them. When the baroclinic time step is too short, an oscillatory behavior not seen in POM is found in ROMS. On the other hand, the ROMS scheme allows the use of a time step much longer than the theoretical CFL condition implies. Therefore, while ROMS code is more than 10 times larger than the POM code and requires about 60% more computation time (on a single processor) per time step, its computational cost per, say one day of integration, is comparable to POM if the longer possible time step is used.

Pressure gradient errors over steep topography in terrain-following ocean models have been an issue of concern for a long time, so reducing such numerical errors are especially needed. The steep seamount test case used in our tests with POM and ROMS is similar to that used in previous studies (Beckmann and Haidvogel, 1993; Mellor et al., 1998). Without external forcing and with only vertical stratification but no horizontal gradients, any velocity (or kinetic energy) is considered a numerical error. Seven pressure gradient algorithms have been compared with the two models: (1) POM with standard Density Jacobian scheme (Mellor et al., 1998), **P-DJ**. (2) POM with sixth-order, Combined Compact Difference scheme (Chu and Fan, 1997), **P-CCD**. (3) ROMS with Finite-volume Pressure Jacobian scheme (Lin, 1997), **R-FPJ**. (4) ROMS with Density Jacobian scheme (Song, 1998) with weighting parameter  $\gamma=0$ , **R-DJ**, which should be equivalent to P-DJ. (5) ROMS with Weighted Density Jacobian scheme (Song, 1998) with optimal weighting parameter  $\gamma=0.125$ , **R-WDJ**, (6) ROMS with Pressure Jacobian scheme using monotonized Quadratic polynomial fits (Shchepetkin and McWilliams, 2001), **R-PJQ**. (7) ROMS with Density Jacobian scheme using monotonized Cubic polynomial fits (Shchepetkin and McWilliams, 2001), **R-DJC**. A comparison between all pressure gradient algorithms is shown in Figure 1, in terms of mean kinetic energy errors.



**Figure 1. Mean kinetic energy errors ( $\text{Kg m}^2 \text{s}^{-2}$ ) for various pressure gradient schemes (described in the text).**

The results indicate several important conclusions: (1) the finite volume pressure Jacobian scheme of Lin (1997) did not perform well in its current configuration in ROMS. (2) When ROMS uses a density Jacobian scheme similar to that used in POM, the errors are somewhat larger than in POM. (3) The

more elaborated schemes (R-WDJ, R-PJQ, R-DJC) reduce errors considerably, in particular, those that use a polynomial fitting approach. (4) The scheme with the smallest error (R-DJC) used in ROMS is comparable in accuracy to the 6th-order scheme (P-CCD) used in POM, but is computationally much more efficient. The magnitude of the pressure gradient error depends also on the horizontal and vertical advection of tracers, time-stepping, and the equation of state for seawater. The more elaborated pressure gradient schemes may work better in combination with high order upstream biased advection schemes. This type of comparisons will continue for other model elements and sub grid scale parameterization in order to help the development efforts, as well as to help users make the best choice of options for particular applications.

## **IMPACT/APPLICATIONS**

The TOMS initiative has already made a significant impact on development efforts by several groups which previously worked independently, but now started to collaborate with each other. The growing numbers of terrain-following ocean model users, including the POM and ROMS communities, as well as operational forecasters will benefit from the development of new numerical algorithms, even before the final version of TOMS is completed.

## **TRANSITIONS**

Full transition of TOMS to operational centers may occur in the far future. However, in the near future, some model algorithms and data assimilation schemes can be used to update existing operational codes; ongoing semi-operational applications of POM and ROMS may also help to make a future transition of TOMS easier.

## **RELATED PROJECTS**

The Princeton group is involved in the development of a hindcast system for the Gulf of Mexico which will benefit from numerical advances such as improving pressure gradient schemes. Studies of wave-induced turbulence by G. Mellor may help to improve future mixing schemes in TOMS. Both, the Princeton and Rutgers groups are part of the international model-intercomparison project, the Dynamics of Overflow Mixing and Entrainment (DOME), which will help to evaluate important test cases for TOMS, relative to other models. There is also ongoing collaboration at Princeton University with model development efforts at the Geophysical Fluid Dynamics Laboratory (NOAA/GFDL).

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