

A Vision for Ocean Circulation Models: Generalized vertical coordinates

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Executive Summary

Recent advances in simulating the ocean through the use of generalized hybrid coordinate modeling techniques have led to a modest proliferation of such models (HIM, HYCOM, HYPOP, Poseidon, and POSUM, among others). These models exploit certain inherent properties of nearly adiabatic flow in the interior of the ocean while attempting to seamlessly transform to more appropriate coordinates near surfaces and in other special regions of interest, such as the coastal zones. While the separate models have made significant advances by exploiting advanced numerical techniques and enhanced physical parameterizations in different ways, it has become apparent that the intellectual diversity fostered through these several efforts is not easily captured or shared to improve models across the board.

This white paper argues for the development of a new ocean modeling environment for generalized, hybrid, vertical coordinate models. Such an environment would:

Accelerate the improvement of such ocean models by

- Unifying the nation's existing isopycnic and hybrid ocean models into a single common code base, based on powerful frameworks such as ESMF. This code base will permit diversity while developing a common language and mechanism for absorbing novel methodologies.
- Exploring the merits of different approaches to represent the important dynamics of the oceans within the generalized vertical coordinate context, leading to best practice recommendations.
- Engaging the wider ocean modeling community to collaborate and assist with the examination and development of best practices in cases where their expertise is relevant for the hybrid coordinates.

Provide a consolidation of models and a path toward a longer-term vision of ocean modeling, including

- A stable, maintainable, production-level code for robust applications using the generalized hybrid coordinates.

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- A single taxonomy and linguistic framework for users and developers.
- A focus for efforts that may evolve in the future to join with modelers currently working in geopotential or sigma coordinates in seeking a larger unification of ocean models.
- A framework that may evolve with those interested in hybrid vertical coordinates combined with alternative, irregular or un-structured horizontal grids.
- Single framework for interfacing with biology, geochemical, or other Earth system models.

This Ocean Modeling Environment will provide dramatically more user- and developer-friendly models and will be an indispensable staging point toward a longer-term vision of ocean modeling.

Introduction

Ocean circulation models are essential tools for understanding, assessing and predicting the global oceans, their role in climate and the Earth system. Much of the uncertainty associated with the prediction of climate can be ascribed to an imperfect knowledge of the oceans and their mechanisms for mitigating or exacerbating changes in the atmosphere and cryosphere. The oceans operate in the climate system to transfer information (heat, salt, chemical constituents) over large distances and long times. Skillful models of the ocean circulation need to transport and preserve these properties correctly. Short-term ocean predictions rely both on the ability to initialize a model to agree with observed conditions, and on the ability of that model to accurately propagate the ocean's state. There is undeniable value from using the same model for prediction as is widely used for long-term simulation and study of the ocean circulation, because it enables each effort to leverage the development and understanding derived from the others.

Generalized hybrid vertical coordinate ocean models are currently used for an increasingly diverse suite of applications, from high resolution now-casting and short-term prediction of the regional ocean state, to global tidal simulations, to ENSO forecasting, to multi-century climate simulations, to theoretical studies of the ocean's dynamics. The various individual decisions to use this class of model were made independently, based on its inherent strengths.

There is now general agreement among ocean modelers that generalized vertical coordinates are desirable for skillful simulations of the ocean (Griffies et al., 2000a). There are well known deficiencies of each of the commonly used vertical coordinates – excessive spurious mixing with sigma- and geopotential-coordinates; lack of resolution and difficulties with the nonlinear equation of state in very weakly stratified interior regions with isopycnal coordinates; pressure gradient errors with sigma-coordinates; and difficulties representing downslope bottom flows with geopotential coordinates. The appropriate generalized vertical coordinate ocean model would minimize each of these liabilities, while providing the flexibility to tailor the model to the specific application.

Vertically Lagrangian solution techniques (ALE, see Margolin, 1997) are well established in the ocean for using an isopycnic vertical coordinate (e.g. Bleck and Smith, 1990, Oberhuber 1993). This combination is uniquely able to avoid spurious diapycnal mixing, even in the limit of geostrophic turbulence (Griffies et al., 2000b) – a critical consideration given the extremely adiabatic nature of the interior ocean and the long timescales upon which the ocean circulation evolves. Isopycnal coordinates are also uniquely valuable for simulating the ocean because both the continuous and vertically discrete forms exactly exhibit the potential vorticity dynamics that are thought to govern the large-scale inviscid and adiabatic ocean circulation[†]. In addition, these techniques have recently been extended to describe hybrid pressure-density vertical coordinates (Bleck, 2002). In the atmosphere, essentially the same techniques have proven highly skillful in a range of simulations that include terrain-following (sigma-) coordinates (Lin, 2003) and in operational predictions (Bleck & Benjamin, 1993). The Lagrangian vertical coordinate approach should be able to emulate the hybrid depth-sigma coordinates, the hybrid density-pressure coordinates that are now being used for some applications, or any one of the single coordinates in wide use, but also go beyond these specific hybrid vertical coordinates to enable the use of a truly general vertical coordinate. A vertically Lagrangian formalism would thus appear to be the most promising avenue for the development of a flexible, state-of-the-art community ocean modeling environment.

*This recognition calls for the development of a **versatile, open-source, community Ocean Modeling Environment using ageneralized hybrid vertical coordinate and Lagrangian solution techniques**. This development effort must also identify and refine best practices or describe trade-offs between alternatives for simulating a range of important ocean processes. The outcome of this development effort would not be a single ocean model, but rather a community collection of ocean modeling code and algorithms from which optimal ocean models for specific applications can be constructed, along with a systematic effort to evaluate the various options.*

What are the advantages of this approach?

The development of a new community-based generalized vertical coordinate Ocean Modeling Environment presents several outstanding opportunities for research, applications and education. The key benefits can be summed up as

- Community Cohesion
- Ingenuity
- Technology
- Flexibility
- Education

[†] Of course, with the ocean's nonlinear equation of state, there is no materially conserved quantity like potential vorticity. Despite this fact, it is still extremely valuable to use a numerical representation of the ocean that would conserve potential vorticity if the equation of state were simpler, as the approximate conservation of potential vorticity provides a powerful constraint on the ocean circulation on timescales of minutes to decades.

Community Cohesion

The advantages of a vertically Lagrangian formalism have led several groups to develop what have turned out to be similar models for the ocean circulation. While coming from various applications and differing roots, these models have more commonality than difference. An active community of investigators meets regularly to share concepts and results, and experience with one model is sometimes carried forth to other codes. However, it has become apparent that too much time is being spent by each group on mundane, replicated and redundant coding, and that the benefits of collaboration far outweigh those of code "ownership". Sharing a common Ocean Modeling Environment will minimize the model development overhead, maximize the usability, and provide a means for harnessing the individual talents of the scientific community on the problem areas each is best suited to address.

Sharing a common modeling environment is only possible in a community with a strong foundation of trust and mutual respect. The Lagrangian vertical coordinate ocean model community has been meeting annually for the past decade to discuss the challenges, experiences and breakthroughs in developing and using the isopycnic and hybrid (pressure-density) coordinate ocean models. The community as a whole has had to grapple with the unique difficulties of isopycnic models, for example striving so that such complications as the ocean's nonlinear equation of state are handled almost as gracefully as with other classes of ocean models. This challenge to the community as a whole has had to be addressed before this class of models could gain wide-spread acceptance, and there has been extensive intellectual cross-fertilization between models. This long experience has led to a strong web of collaborations, many evidenced in publications, and out of it has emerged a community with a strong base of mutual trust and respect, and the ability to critically and candidly examine the virtues and faults of various approaches without endangering the community's cohesion. In this respect, the Lagrangian-vertical coordinate ocean modeling community is ideally suited for the transition to a community modeling environment.

The ideals of a community based ocean modeling environment have been long promoted, but this is perhaps the first truly community-generated initiative to consolidate modeling efforts and share ownership and development of a significant computing resource for the nation and the world's oceanographic community.

Ingenuity

The Ocean Modeling Environment will be a base for the future exploration of novel modeling concepts, the more rapid improvement of large scale circulation models, and a stable base for the development of new application services built around a core model framework that can be maintained at the cutting edge of the science. It will provide a framework for experimentation and rapid implementation of improvements in the representation of physical processes in ocean models.

For example, innovative features that the Lagrangian vertical coordinate Ocean Modeling Environment models might explore include, but are not limited to:

- Multi-level refinements to the representation of surface mixed layers
- alternative vertical coordinates (orthobaric or iso-neutral surfaces)
- effects of nonlinearities in the equation of state, such as thermobaricity and cabbeling
- explicit resolution and modeling of bottom boundary currents,
- thermosteric sea level rise and coastal flooding
- direct calculation of internal and external tides
- multi-model ensembles and interactive ensembles
- active biogeochemical models

The Ocean Modeling Environment will furnish the capability to interchange and combine and modify choices of vertical coordinate, physical parameterizations, algorithms, parameter settings, and so on. This is in contrast with the usual single model consisting of a fixed set of parameterizations and algorithms, perhaps with some restricted freedom in the setting of parameters, but with very limited user options to experiment with model modification. The Ocean Modeling Environment will not merely be a collaboration of several groups to consolidate the options of various hybrid vertical coordinate models into a single code. Though this by itself would make a significant contribution to ocean modeling, it would miss a far larger opportunity to explore new combinations of ideas.

It is essential to maintain and extend the diversity of available algorithms. The diverse collection of techniques is the gene pool of future ocean models. A rich pool provides the best prospect for selecting the models that are optimal for answering specific questions about the ocean. By comparing the performance of a rich array of configurations, the community will be able to breed ocean models that are most generally skillful at representing the broad assortment of physical processes that are important in the simulation of a system as complicated as the ocean circulation. The danger of code proliferation - that it may lead to modeling camps isolated from each other - is counteracted by the provision of an overarching Ocean Modeling Environment.

The grand idea driving the Ocean Modeling Environment is that it should foster the ingenuity and innovativeness of the user, rather than restricting it into well-worn channels.

Technology

Another significant factor in the development of the new community Ocean Modeling Environment is the ability to exploit the deployment of new technology rapidly and effectively. Foremost among these are the Earth System Modeling Framework (ESMF) and the Common Component Architecture (CCA). These technologies work together to provide the models insulation from hardware architecture (via ESMF's infrastructure level) and performance issues and to provide a powerful and effective means for building robust and portable model systems that can easily be coupled to atmosphere models, sea-ice models, and data assimilation systems (via ESMF's superstructure level). This development effort would be one of the first model systems whose code is built from the

ground up on ESMF, and should be compliant with the emerging standards for model interoperability, such as the PRISM standards in Europe.

The common software framework will also permit the new community ocean models to be developed with mature data assimilation and initialization methods, such as those currently used at NASA GMAO (and incorporated into ESMF) and NRL Stennis. The use of a common framework will facilitate further research into ensemble Kalman filter and other data assimilation techniques and application of remote sensing for model initialization and verification. Rich nesting capabilities would also accrue directly from using ESMF.

The commitment to ESMF and development through a large community would ensure that ocean modeling applications can be built and maintained for the long-term. Whether the application is coastal coupled forecast systems, or IPCC global climate assessments, it demands stability and long-term support. The open-source software movement has shown that a committed team of interested investigators representing a number of large institutions can provide a secure and long-lasting basis for support.

Flexibility

The development of a generalized-Lagrangian vertical coordinate Ocean Modeling Environment will facilitate the development of model systems having depth, pressure, fractional depth (sigma), isopycnal or combinations of these as the basis for vertical discretization. For example, it might prove valuable to have a model that includes deep ocean regions in isopycnal coordinates and coastal and shelf regions in sigma or pressure coordinates. While there are special challenges to any of these more exotic combinations of choices, the reward may be great, and the exploitation of a common Ocean Modeling Environment will mean that developments by one group for a specialized application can be readily shared with all users. Moreover, the experience in atmospheric models has been that sigma- and pressure-coordinate models based upon Lagrangian vertical coordinate techniques are competitive with, or even superior to, models using the traditional Eulerian techniques (e.g. Lin, 2003). There is every reason to expect that oceanic situation will be similar.

Education

The emergence of a common modeling environment for generalized Lagrangian coordinate ocean modeling should provide concrete benefits to the nation's need to develop the next generation of scientists. The full ocean models that are used for oceanic predictions or climate studies are much more complicated than is often appropriate for many pedagogical purposes or for idealized studies. As a result, many students are not exposed to the models that are used in practice. If a simplified selection of the full code-base for illustrative or idealized simulations can be included along with a very user-friendly interface, one can envision the widespread use of the base code in graduate oceanographic education. For developing a proficient ocean modeling community, for maintaining community cohesion, and for speeding the integration of recent graduates

into the scientific modeling workforce, there is no substitute for training students with the same code-base as is used for real applications.

Why now?

There are several reasons why this generalized hybrid vertical coordinate community Ocean Modeling Environment should be developed now: (1) Hybrid vertical coordinate ocean models are being used for an increasingly large array of oceanic studies and applications; (2) The Earth System Modeling Framework (ESMF) will enable ocean modeling code to be written with greater flexibility while isolating the models from the details of the hardware upon which they are run; (3) All of the potential predecessor models are committed to adopting ESMF, and simultaneously converting to the common code base will mean much less disruption for both the model users and developers than if the transition to ESMF and the transition to the shared code base were to happen separately; and (4) Most importantly, virtually the entire hybrid vertical coordinate ocean model development community is genuinely interested in channeling their currently disparate efforts into a community Ocean Modeling Environment.

Why Limited to Layered Models?

The vision that is presented here is one of an initial merge of hybrid (isopycnal) models into a common framework. Such frameworks could be envisioned to embrace sigma- and geopotential-based coordinate models into a single environment. While we embrace an eventual goal of accommodating many models into the framework, a close examination of the hybrid coordinate models reveals that there are many scientific issues facing layered ocean models. The impetus for this effort centers around a desire to capture the best practices and differences between the extant layered models in order to accelerate the development of improvements to the models and to cull non-competitive options. For the next few years, such focused work on readily achievable consolidations and extensions of current practice through a succession of viable models is a prudent staging strategy toward the more challenging broad consolidation of ocean modeling practice in the longer term.

What is the 10-year vision?

The 10-year vision is to have a broad unification of ocean modeling practice by collecting the expertise of the current sigma-, geopotential-, and isopycnic/hybrid- coordinate models in a single software framework. This will allow the greatest possible flexibility for users and synergies for model developers.

There are currently efforts to unify the terrain-following (sigma-) models through the TOMS effort. In addition, there are ongoing efforts to promote much tighter coordination between the GFDL/MOM and MIT model groups over the next 3-years. The proposed initiative is to propose a complementary effort to unify the generalized hybrid coordinate development teams into a single code base within 3-years.

The next step, which has been endorsed in principle by the key model developers from each of the three existing classes (including MOM, MIT, HIM, HYCOM/MICOM,

POP/HYPOP, Poseidon, POSUM, and ROMS/TOMS), is to unify all of the three model classes into a generalized ocean modeling environment, within a time-frame of 5-10 years.

Why should support be multi-agency?

Different agencies have differing but complementary ocean modeling interests in such areas as short-term ocean forecasting and nowcasting, state estimation, seasonal to interannual forecasts, interpretation of satellite data, global and regional climate prediction, and basic studies of the ocean's dynamics, as well as in the use of ocean models as educational tools. A broad base of agency support will both ensure that these varied interests will be addressed, and it will lessen the burden on any one Federal agency. Also, a broad base of agency support may be indispensable for fully engaging all of the relevant existing Federal activities; these activities currently exist within Navy, NOAA, DOE, and NASA labs.

Perhaps a more compelling reason for multi-agency support lies with the human dynamics of community model development. Centralized support will reinforce the concept of a team effort, and reward individuals for continuing cooperation, rather than providing incentive for withdrawing from the project.

Finally, we estimate that a viable effort would cost roughly \$1.5 million/year, in addition to the in-kind support from key institutions. Funding of this magnitude can be achieved most easily with multi-agency support.

Measures of Success:

There are a number of specific objectives by which the success of the advocated effort will be measurable:

- (1) The voluntary participation of a substantial portion of the nation's existing isopycnal and Lagrangian vertical coordinate model development community in contributing to and transitioning to a shared, open source community Ocean Modeling Environment.
- (2) Collaboration from the nation's broader ocean model development community to consult on software design and to partner in the assessment of algorithmic best-practices for ocean modeling and refinement and extension of existing algorithmic capabilities.
- (3) Contributions of new capabilities or algorithmic alternatives from beyond the circle of the key developers of existing models.
- (4) The development of a code base that is easy to configure and use for a variety of applications. The documentation accompanying this code base must be clear, consistent, and explicit. The continued quality of this code base must be assured by an effective and sustainable Ocean Modeling Environment governance structure.
- (5) Widespread adoption of the code-base for ocean applications.
- (6) The development of extensive best-practice guidance for representing important processes to guide the construction of specific ocean modeling

applications. This would include critical evaluation of previously unavailable algorithmic combinations, and it would almost certainly lead to improvements to oceanic applications based on these new combinations.

- (7) The development and adoption of a selection of pedagogically useful examples derived from the Ocean Modeling Environment code base.

If successful, this initiative will go far toward transforming ocean models into the “handy, graceful tools, easily and promptly applicable to any well posed scientific question about the ocean, usable by anyone anywhere, and with well established uncertainty estimates” that are called for in the WOCE final report (Hallberg and McWilliams, 2001). The greatest value to accrue from developing a Lagrangian vertical coordinate Ocean Modeling Environment will be in dramatically reducing the human costs of developing and using ocean models.

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