A Historical Introduction to MOM

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Abstract

The Modular Ocean Model (MOM) is a numerical code used for simulating the ocean circulation, from small scale process studies to large scale general circulation predictions and earth system modeling. MOM was developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) in the early 1990s and it continues to be developed today at GFDL and through national and international collaborations. Its lineage dates to the 1960s and 1970s from the pioneering work of Kirk Bryan, Michael Cox, Albert Semtner, and collaborators. In this document, we present a history of MOM from the perspective of its development and its use. Our aim is not for completeness, but rather to highlight certain milestones that greatly impacted the code development and use.

Code details, numerical methods, physical parameterizations, test cases, and documentation have evolved tremendously across each MOM version. This evolution was largely impacted by the changing nature of oceanography and climate science, and the quest to make efficient use of new paradigms in computational software and hardware tools. Each MOM version represented the cutting-edge of ocean model tools of its day, leading up to the present version, MOM6. Furthermore, each MOM version has been developed with an emphasis on scientific integrity, code transparency, and flexibility across a broad suite of science and operational applications.

Introduction

The Modular Ocean Model (MOM) is a numerical code based on the ocean primitive equations. It is used to simulate the ocean circulation in both idealized and realistic configurations. MOM was originally developed at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) in the early 1990s. Upon the release of MOM1 by Ronald Pacanowski, Keith Dixon, and Anthony Rosati, it quickly became one of the most popular dynamical ocean models world-wide.

In the early 1990s, it was very unusual for institutions to freely release to the public their climate model codes. The common assumption was that doing so would present too much work for the developers to support outside users, without receiving sufficient intellectual feedback. Furthermore, codes that were public typically had little documentation of either the code or the run scripts needed to integrate the model on a computer.

The release of MOM changed this situation by providing extensive documentation and a wide variety of run scripts and test cases. This level of transparency, and the high level of success using MOM based ocean models for climate science, ocean forecasting, and state estimation led to its wide popularity. It furthermore put to rest the cost/benefit concerns, as its public release led to extensive collaborations and science resulting from efforts to support the MOM community both within GFDL and abroad. Thus was established a new paradigm in community climate model tools that is largely followed to this day by other ocean and climate models.

Growth of MOM through the 2000s

By the early 2000's, MOM had more than a 1000 users, though the precise number is unknown given its open-source and free distribution. A support community developed to help relatively novice users find answers to their questions, and to support interaction among the various users with all degrees of expertise. GFDL scientists have overseen this process and encouraged its development. Again, this type of community centered support was novel for the time, and it again pioneered what is now a standard for the community.

Along with user support for running MOM, extensive documentation of the code and run scripts was provided with each MOM release. The documentation greatly helped experienced ocean scientists and students alike to use MOM for meaningful and intellectually informed scientific studies. Quite generally, MOM documentation has aimed to provide the community with a means to understand the foundation of the model code, including its physical parameterizations, numerical methods, diagnostics, and computational elements. The monograph from Griffies (2004) was a direct result of this effort. Writing such documentation has helped to establish an intellectual basis for MOM, and in turn for ocean climate modeling.

Since GFDL scientists and engineers have been, and remain, the main drivers for many (but not all) of the model advances, MOM code development closely followed the model configurations and computers used by GFDL scientists. However, MOM developers have remained careful not to encode machine specific instructions into the code. MOM has therefore been ported relatively easily to machines that are different from those used by GFDL. This attribute has facilitated MOM's adaptation by many research groups nationally and internationally, and it in turn has supported numerous collaborative projects using MOM across many computational platforms.

MOM as a code with example model configurations

We distinguish between a model configuration and the code used to develop and run the model. MOM is for the most part a code. With numerous parameter options and associated tools released as part of MOM, the code can be configured in many different ways. These model configurations differ, for example, in their geographical domain, boundary conditions, grid resolution, subgrid scale mixing schemes, numerical advection scheme, etc. Such details are largely determined by the chosen application, ranging from regional process studies to global climate model predictions. Establishing these details requires extensive understanding of the physics and numerics of the code, and the scientific application. Numerous test configurations are released as part of the various MOM versions. These tests aim to assist the researcher interested in setting up a new configuration, or by providing a configuration ``off the shelf'' that may be of use for a specific application.

Remainder of this document

The rest of this document describes the history of MOM, starting with development and use of the Bryan-Cox code in the early 1960's and extending through the 1990's. It then goes through each release of MOM starting in 1991, extending up to present work on MOM6. We present key developments and developers associated with each release.

Bryan-Cox Ocean Model Code

Early in the 1960's, Joe Smagorinsky, GFDL's first director (1955-1983), recognized the importance of developing a world ocean circulation model for use in studying climate. To lead this development effort, he hired Kirk Bryan, who completed his PhD at MIT under Ed Lorenz. An early emphasis of Bryan's research concerned the ability of numerical models to help understand nonlinear effects from strong boundary currents (Bryan 1963). During these early years, Bryan also helped quantify the importance of the ocean in climate by studying the transport of heat (Bryan 1962). Poleward, and vertical, heat transport are key reasons for why the ocean is so important for the earth's climate.

Towards a World Ocean Model

Development of a numerical model capable of simulating the World Ocean was a massive project. No one else had done so before, and there were many issues to address, some practical and some fundamental. Bryan was able to incorporate many of the ideas being tested in the atmospheric simulations actively pursued at GFDL. Critical to the achievement of this task was the input of Mike Cox, who started employment at GFDL as a computer operator but quickly showed talent for numerical modeling.

By the second half of the 1960s, Bryan and Cox completed their prototype World Ocean model configurations (Bryan and Cox 1967, 1968a, 1968b). To accomplish this task, they had to make assumptions to allow efficient numerical integration using computers available in the 1960s. One of these assumptions was a rigid lid for the ocean surface. The rigid lid eliminates fast external mode gravity waves found in the real ocean, thus allowing for longer time steps required to make the model of practical use for climate studies (Bryan 1969). A second order numerical scheme was used along with centered advection to remove nonlinear instabilities (Phillips 1958, Bryan 1966). They chose the Arakawa B-grid for staggering of tracer and velocity variables, allowing for more accurate numerical calculations of geostrophically balanced motion using the coarse resolution allowed by computers of the day. Bryan (1969) described this numerical algorithm, and the code became known as the Bryan-Cox model.

The primary GFDL application of the Bryan-Cox model was for use as the ocean component of a coupled atmosphere-ocean general circulation model (AOGCMs). One of the important milestones in climate science is the publication of Manabe and Bryan (1969) describing results obtained from the world's first AOGCM. This model was way ahead of its time. Indeed, it was not until the 1990's that AOGCMs became the workhorse used by researchers to study climate and climate change.

During the 1970s, Bryan's group worked on addressing problems seen in early model integrations. In particular, Bryan and Lewis (1979) showed a credible simulation of the world ocean water masses where the model was time integrated over a long time period sufficient to establish deep water properties. One of their advances was the use of a vertically varying tracer diffusion coefficient. This ``Bryan-Lewis'' diffusivity was an early recognition of how important vertical mixing processes are in establishing ocean water mass distributions. This ocean model configuration, with some further modifications such as incorporation of the Cox (1987b) isopycnal diffusion scheme, was the basis for the ocean component of the R15 climate model used by Manabe and his group during the 1980s and 1990s.

An important branch code from that used at GFDL was developed by Bert Semtner after he completed his PhD at Princeton. His code (Semtner, 1974) was notable for having incorporated arbitrary land-sea masking, and for upgrades to the efficiency. These improvements influenced later versions of the ocean code used at GFDL.

First community ocean model code and manual

GFDL during the 1970s and 1980s was a haven for oceanographers interested in the revolutionary simulations produced by the lab. The ocean code remained under control of GFDL, with no use outside of the lab. However, in 1984, Mike Cox took the novel and revolutionary step of making the Bryan-Cox code freely available to the public. Use of the Bryan-Cox model quickly spread through the ocean modeling community, well beyond GFDL.

In addition to code, Cox provided a manual describing the mathematical equations and numerical methods forming the basis for the ocean model code. Although not as comprehensive as modern documentation, the Cox manual proved incredibly valuable in communicating the rationale for various features in the code. In so doing, the code became intellectually transparent to a broader community of numericists and theorists alike, particularly those averse to reading Fortran code written by someone else. Indeed, many students learned about the ocean primitive equations by reading the Cox manual.

The Cox code and its documentation proved valuable for entraining experts from abroad interested in making use of the code as a starting point for their own ideas. For example, in the UK, Peter Killworth and David Webb made use of the Cox code to establish the Fine Resolution Antarctic Model (FRAM), and later the Ocean Circulation and Climate Advanced Model (OCCAM). These efforts led to an early implementation of an explicit free surface method (Killworth et al 1991) and open boundary conditions (Stevens 1991). Such methods later made their way back into MOM, thus providing early examples of the power of community collaborations with code development. Another example is the French OPA project, later renamed NEMO, which had its seeds in the time that Pascale Delecluse spent in the 1980s working with GFDL oceanographers.

The Cox (1987b) rotated diffusion operator (i.e., isopycnal diffusion) is an important feature added to the Bryan-Cox code in response to community suggestions and observational evidence. This operator built upon theoretical work of Redi (1982) at GFDL, and earlier work of Solomon (1971). The rotated diffusion operator aimed to respect growing observational evidence (e.g., Veronis 1975) that tracers are largely stirred by mesoscale eddies along isopycnals (today more precisely known as neutral directions), rather than along the geopotential surfaces to which the model vertical coordinate was oriented (z-model). Cox's implementation of rotated diffusion nurtured further community research into how to formulate a closure for the tracer equation that appreciates the role of unresolved transient mesoscale eddies. One such development was the Gent and McWilliams (1990) paper, which forms the basis for many of the mesoscale eddy parameterizations in modern ocean climate models (see historical review by Gent 2011).

We note that not everyone at GFDL backed the effort by Cox to support a broader community outside of GFDL. There were concerns that such support for the code would take too much time, and that GFDL would not get much in return. Such ``one-way street'' concerns, however, were later proven incorrect. There are numerous examples of collaborations and contributions, some mentioned above and others discussed later, serving to enhance the science available from the code.

Research efforts impacting on development and use of the Bryan-Cox code

Until the middle of the 1990s, GFDL was largely organized into research groups led by a principal investigator, with other scientists and technical support staff aligned with the focus of the PI. Three GFDL science groups made great use of the Bryan-Cox code for their research throughout this time. The Ocean Group, led by Bryan, was focused on understanding ocean processes, with particular emphasis on the ocean's role in climate. Among this group for sometime was George Philander, who focused on tropical ocean dynamics. Suki Manabe led the climate group, with his group using the ocean model as part of the coupled climate models for climate dynamics and climate change studies. Finally, the prediction group, led by Kiku Miyakoda, made use of the ocean model for coupled climate system predictions focused on seasonal to interannual phenomena.

Within this research environment, there were numerous landmark studies during the 1970s through 1990s that made use of the Bryan-Cox code, or its predecessors. We list here a selection of studies that provide a sense for the exciting and pioneering efforts facilitated by ocean and climate modeling at GFDL during this time. Such studies provided critical feedback towards further model development. This feedback made clear that science going into a model, in support of its development, is greatly enhanced by science emergent from use of the model to help understand the ocean and climate. Intimate interactions between model development and model use remain fundamental to the success of GFDL modeling.

- **Southern Ocean**: Gill and Bryan (1971) performed the first primitive equation simulations focused on Southern Ocean dynamics, with particular focus on impacts from the Drake Passage. Even with the rather poor resolution of the model used then, certain of the conclusions have stood the test of time. This study was conducted during a sabbatical visit to GFDL by Adrian Gill.
- **Dynamical ocean spin-up:** David Anderson and Jurgen Willebrand each did post-doctoral studies at GFDL, with their efforts leading to publication of Anderson, Bryan, Gill, and Pacanowski (1979) and Willebrand, Philander, and Pacanowski (1980), each of which examined the transient response and spin-up of the ocean under atmospheric forcing. Many of their insights have become standard textbook material for today's physical oceanography.
- **Tropical oceanography:** George Philander and Ron Pacanowski had a longstanding collaboration, which in the 1980s was focused on understanding tropical ocean circulation and its role in ENSO (Philander 1991). Notably, the turbulent mixing scheme from Pacanowski and Philander (1981) was a direct result of their work in this area.
- **Mesoscale eddies and thermocline theory**: Claus Boning did his post-doctoral studies at Princeton, during which time he collaborated with Mike Cox. Boning and Cox (1988) is an early example of how idealized primitive equation simulations using the Bryan-Cox code can be of use to help understand mesoscale eddy processes, including impacts from topography. Their study was partly an extension of earlier work by Bryan and Cox (1984) and Cox (1985, 1987a), aiming to understand, through numerical simulations, ideas of the ventilated thermocline of Luyten, Pedlosky, and Stommel (1983).
- **Vertical mixing and T/S boundary conditions:** Frank Bryan (no relation to Kirk Bryan) did his PhD at Princeton; he was the first student supervised by Jorge Sarmiento. Partly motivated by discussions with Claus Rooth, who was visiting Princeton in the early 1980s, Frank Bryan considered the role of vertical mixing (Bryan 1987) and surface boundary conditions (Bryan 1986) in the ocean's overturning circulation. Bryan's thesis work used a now classic idealized "thermohaline sector model" configuration that launched many further studies of its kind during the subsequent decade. His 1986 paper is particularly notable for providing the first primitive equation simulation exhibiting multiple equilibria for the overturning circulation, following on a result from Stommel (1961) realized in a semi-analytic two-box model.
- **Multiple equilibria of ocean climate:** The study from Bryan (1987) was soon followed by Manabe and Stouffer (1988), whose coupled model simulations also exhibited multiple equilibria. Both papers attracted great attention particularly from the paleoclimate community as providing new hypotheses for the role of ocean circulation changes in past climate states.
- **Upper ocean and air-sea interactions:** Rosati and Miyakoda (1988) pioneered the use of an upper ocean boundary layer scheme within a global climate predication model. They also paid particular attention to the physics of air-sea interaction of importance for seasonal to interannual climate fluctuations. This work proved very important for later development of the Coordinated Ocean-ice Reference Experiment (CORE) (Griffies et al., 2009).
- **Ocean Data Assimilation**: Derber and Rosati (1989) developed the first ocean data assimilation system within the Cox-code, thus providing a key tool needed for ocean initialization and ocean prediction.

- **World Ocean watermasses:** Just prior to his death, Cox (1989) provided a water mass study that updated and refined the earlier work of Bryan and Lewis (1979). The Cox (1989) paper proved influential in plans for the World Ocean Circulation Experiment (WOCE).
- **Ocean tracers**: Toggweiler and Sarmiento were pushing the use of ocean models for studying ocean tracers, prompted largely by the increasing measurements of tracers during the 1980s. The study by Toggweiler, Dixon, and Bryan (1989) exemplified this work, laying the foundations for many future model studies of ocean tracers and their distributions throughout the World Ocean.
- **Atlantic overturning circulation**: GFDL scientists have written many pioneering studies of the Atlantic overturning circulation (AMOC). A notable early entry in this area is that from Delworth, Manabe, and Stouffer (1993), who were the first to document multi-decadal AMOC fluctuations in the R15 climate model. Griffies and Bryan (1997) then examined predictability of these fluctuations. Both studies remain influential in the AMOC community to this day.
- **Transient climate change**: Manabe and his group used the R15 AOGCM to perform some of the first studies on transient climate change in response to increasing greenhouse gases (e.g. Stouffer et al. 1989). These studies established the idea that places in the ocean where deep waters are formed are resistant to warming. This role of the high latitude oceans in turn leads to a very different pattern in the surface air temperature response than seen in the earlier equilibrium response studies.

MOM circa 1991-2012

Besides research at GFDL, the Bryan-Cox code was used nationally and internationally for important studies, such as those mentioned earlier by UK scientists for FRAM and OCCAM, as well as climate modeling efforts at NCAR. But early in the 1990s, with the release of MOM1, many researchers embraced this new code, which was largely based on Bryan-Cox, but which had enhanced features and code style furthering its flexibility and transparency. In this section, we provide a summary of the various MOM versions, highlighting certain of the features that distinguish the releases. We do not aim for completeness with citations for papers making use of the codes. Doing so would inevitably miss important papers due to our limited exposure to the huge numbers of studies making use of various MOM releases around the planet.

MOM1 (1991)

Mike Cox died from cancer in 1989 (see Bryan 1991 for an account of Cox's contribution to oceanography). After his untimely passing, Ron Pacanowski, Keith Dixon, and Tony Rosati took up the reigns of ocean model development at GFDL. The dynamical core of MOM1 (Pacanowski, Dixon, and Rosati, 1991) followed the basics detailed in Bryan (1969). However, the code was pushed forward by making use of a more modular style available with Fortran 77. Additionally, a number of physical parameterizations were added to enhance the model's functionality for various studies. These new options included the following.

- **Tropical ocean mixing**: Pacanowski-Philander (1981) vertical mixing scheme, which was developed for studies of tropical circulation.

- **Boundary layer physics:** Mellor-Yamada (1982) turbulence closure for boundary layer processes, which was developed in collaboration with George Mellor at Princeton University.
- **Lateral friction:** The Smagorinsky (1963) lateral friction scheme was implemented through the work of Rosati and Miyakoda (1988). This scheme was originally developed for atmospheric models and has seen widespread use in Large Eddy Simulations.
- **Elliptic solver**: Cox (1984) used a relaxation methods to solve the rigid lid elliptic equation, whereas MOM1 made use of the more efficient and accurate conjugate gradient method.

The rewritten MOM1 code was easier to understand and use than the earlier Bryan-Cox code, thus leading to even more researchers and students making use of MOM1 for ocean and climate science. Furthermore, as with the Cox-code, MOM1 engendered support from a broad national and international community. This time was well before routine use of code repositories and version control. Rather, it was a time when code was maintained by a few ``gatekeepers'' who handled bug fixes and user support questions through email and post-mail.

With the benefit of hindsight, it seems natural that Pacanowski, Dixon, and Rosati should have embarked on their new vision for the GFDL ocean model, one that embraces updated coding practices and enhanced code clarity and documentation. However, as with the public release of the Bryan-Cox code in 1984, there were dissenting views within GFDL, largely based on concerns that energies should not be spent supporting a broader community. However, it quickly became clear that MOM1 was a huge success, as the MOM community facilitated widespread collaborations and enhanced science opportunities for GFDL and the broader community. In effect, there was no turning back!

During the 1990s, the National Center for Atmospheric research (NCAR) had its own ocean model, the NCAR CSM Ocean Model (NCOM). NCOM was a derivative of MOM1, with NCAR incorporating certain of its physical parameterizations into the core. NCOM development was led by Rick Smith and John Dukowicz at Los Alamos National Laboratory (LANL). In support of their efforts, they furthered collaborations between NCAR, LANL, and GFDL. Examples of work resulting from these collaborations include development of a new barotropic solver (the Dukowicz and Smith 1994 implicit free surface); the KPP boundary layer scheme (Large et al. 1994); the Gent and McWilliams (1990) mesoscale parameterization; the Griffies et al (1998) neutral diffusion scheme; and the Griffies (1998) skew diffusion reformulation of Gent and McWilliams. Throughout these efforts, scientists at each of the three labs held discussions on how to optimally merge their work to help build mutually agreeable ongoing collaborations. Unfortunately, efforts to formalize the collaboration failed. As a result, the two efforts split, with the LANL group releasing a version of MOM1 called POP (Parallel Ocean Program), and GFDL continuing with MOM. POP is still used in the Community Earth System Model (CESM) AOGCMs (e.g., Smith and Gent 2004).

MOM2 (1995)

As noted above, after the code rewrite and enhancement leading to MOM1, GFDL received significant positive feedback from the international modeling community. MOM code development continued and in 1995, Ron Pacanowski and Charlie Goldberg released the MOM2 code and manual (Pacanowski 1996). The main advances made for MOM2 include the following.

- **Memory window**: In addition to the general code improvements, a number of machine and model improvements were made. The memory window was motivated by trying to take advantage of the small number of processors (order 10) available on the computer at GFDL. It allowed breaking the single slab of the Cox-Semtner model (which did not parallelize well) into multiple slabs (one per processor) to achieve parallelization. Hence, through namelist options, the user could either run the model with all the memory available to a given processor (typical for vector machines) or just have a subset of the memory available (required by distributed memory machines).
- **Tracer manager:** Another development around this time was inclusion of a "tracer manager" in MOM. This feature allowed developers to easily put new tracers into the code and then use the model to explore science questions. The ocean biogeochemical community made particular use of this feature (e.g. Toggweiler and Carson 1995). This tracer work built on earlier efforts which used the original Bryan-Cox code or MOM1 (e.g. Toggweiler et al. 1989, Dixon et al. 1996).
- **Free surface methods:** Two free surface methods were implemented in MOM2, representing some of the first examples of methods/parameterizations from outside GFDL coming back and positively influencing MOM development. One free surface method was based on the implicit scheme from Los Alamos (Dukowicz and Smith, 1994). The other was an explicit scheme from the UK (Killworth et al 1991). The goal of both schemes was to relax the rigid lid assumption in the original Bryan-Cox model (Bryan 1969), which was invoked for computational efficiency reasons based on the computer constraints of the day. By relaxing the rigid lid assumption, the model dynamics could become more realistic, in particular allowing the model to incorporate astronomical tidal forcing. Additionally, when moving to the fully explicit approach, the model no longer required an elliptic solver for the barotropic mode, thus enhancing the model's scaling behavior on many of the day's parallel computers. Variations on such split-explicit free surface methods are now common throughout the ocean modeling community.

- **Topography generation:** MOM2 provided preprocessing code to develop the land/sea mask and bottom topography for new model configurations, thus facilitating the use of MOM2 for many different idealized and realistic applications.

- **User manual:** The user manual was much improved in the MOM2 release. Again, this enhancement allowed users access to the internal workings of the model and the intellectual foundations for the methods and parameterizations.

MOM3 (1999)

MOM3 was released in 1999, with Pacanowski and Griffies the main developers. The user manual (Pacanowski and Griffies, 1999) continued to grow and become more extensive. Several new parameterizations were included, including the following.

- **Neutral physics parameterizations:** The neutral diffusion scheme of Griffies et al (1998) was introduced in MOM3, resulting from a close collaboration between GFDL and LANL. This formulation resolved a pernicious numerical instability plaguing the isopycnal diffusion scheme originally implemented by Cox (1987b). Griffies (1998) followed with a reformulation of the Gent and McWilliams (1990) parameterization that also reduced certain problematic issues with the original NCAR method.

- **Topography**: Partial bottom steps of Pacanowski and Gnanadesikan (1998) were added, with this work motivated by the work of Adcroft et al. (1997) using the MITgcm. Partial steps allow for a more realistic representation of the bottom topography relative to the older fixed thickness cells.
- **Lateral friction**: An updated version of the Smagorinsky friction scheme was introduced by Griffies and Hallberg (2000), including an option for use in a biharmonic operator rather than the traditional Laplacian operator.
- **Explicit free-surface:** Griffies et al. (2001) introduced a more stable and efficient explicit free surface method that resolved problems encountered in realistic simulations with either the Dukowicz and Smith (1994) implicit method or the Killworth et al. (1991) explicit method. It was notable that the explicit free surface was found to be more efficient on parallel machines that the rigid lid approach.

MOM4 (2003)

Griffies, Harrison, Pacanowski and Rosati released MOM4.0 in 2004.. Key characteristics of this code include the following.

- **2d domain decomposition:** The memory window approach in MOM2 and MOM3 was replaced in MOM4 with a 2D domain decomposition based on halos in the horizontal directions. The 2D domain decomposition method was implemented for POP at Los Alamos by Rick Smith and John Dukowicz, and at GFDL by Robert Hallberg for the HIM isopycnal model. It proved far simpler than the memory window, and it became practical at GFDL when the amount of memory per processor allowed computers to handle higher resolution global models. 2D decomposition remains the basic method in MOM5 and MOM6 for parallelization.
- **Time stepping**: The time stepping scheme was changed to a 2-level staggered scheme to provide conservative tracer evolution to within computational truncation error, even with use of the nonlinear free surface and in the presence of real water fluxes. This method was inspired by approaches used by the Hallberg Isopycnal Model (HIM) (as described by Hallberg (1997)) and the MITgcm. Additionally, as detailed in Griffies et al (2005), the new time stepping scheme reduced the model cost by a factor of two, in effect doubling the time step available relative to the leapfrog scheme.
- **Generalized orthogonal horizontal grids:** The horizontal grid structure and finite difference equations were generalized to allow for arbitrary orthogonal coordinates. Subsequent to this feature, GFDL climate models made use of the elegant tripolar grid from Murray (1996). With this grid, the Arctic Ocean coordinate singularity found with spherical latitude/longitude grids is split into two singularities that are safely moved into land. Keeping the coordinate singularities in land (one in Siberia, one in Canada, and one at the South Pole) eliminated the

need for Arctic polar filtering of dynamical fields, thus enhancing the integrity of Arctic circulation features.

- **Open Boundary Conditions:** A robust and flexible suite of open boundary condition (OBC) options is essential for regional applications. Collaborations with Martin Schmidt in Germany and Michael Herzfeld in Australia resulted in the implementation of a sophisticated suite of OBC options (Herzfeld et al 2011), offering far more useful options for regional modeling than the original scheme of Stevens (1991).
- **Astronomical tide forcing:** Efforts by Harper Simmons in Alaska and Russell Fiedler in Australia led to implementation of an 8-constituent astronomical tide forcing scheme. Schiller and Fiedler (2007) illustrated the effects in a global model configuration.
- **Ocean biogeochemistry:** A fully developed ocean biogeochemical model (BGC) was included in this release (Dunne et al. 2012, 2013). This model simulates ocean ecology as well as important chemical life cycles. This ocean BGC, along with terrestrial BGC components, allowed the development of NOAA's first earth system model (ESM). Notable efforts from Jorge Sarmiento's group at Princeton University, particularly Rick Slater, were critical to the success of this code.
- **Diagnostic manager**: As part of the new GFDL Flexible Modeling System (FMS), MOM4 make use of a diagnostic manager, enabling far simpler capabilities to enable the growing list of diagnostic options in MOM.
- **User manual and book**: The user manual continued to be updated (Griffies, Harrison, Pacanowski, Rosati, 2004), with a monograph by Griffies (2004) more formally documenting the various algorithms used in MOM. This book has been used by many to help understand the various dynamical and physical equations and methods used in ocean climate models.

MOM4.1 (2007)

Griffies released MOM4.1 in 2007 along with an updated manual (Griffies 2007). Key features of this release include the following.

- **Generalized level vertical coordinates:** An option for a generalized level vertical coordinate including Boussinesq and non-Boussinesq options (z* and p*). The z* vertical coordinate became the standard coordinate used in climate and earth system models at GFDL, with such models contributing to the Coupled Model Intercomparison Project Versions 3 and 5 (CMIP3, CMIP5).
- **CM2.1 test case:** The MOM4.1 release provided an atmosphere-ocean general circulation model (AOGCM) (the CM2.1 model of Delworth et al 2006).

MOM5 (2012)

MOM5 was released by Griffies in 2012 along with an updated manual (Griffies 2012).

- **Climate and ESM test cases:** MOM5 included two new GFDL global coupled models as test cases: CM3 (Donner et al 2011, Griffies et al 2011), which is an AOGCM, and ESM2M (Dunne et al, 2012, 2013), which is an Earth System Model (ESM).
- **Coarse resolution ESM test case:** Additional test cases were provided to test these new models, including a relatively coarse resolution earth system model (CM2Mc) (Galbraith et al 2012).
- **New biogeochemistry options**: Along with the ESMs, two variants of ocean biogeochemical (BGC) models were also included in the release. One was the TOPAZ model developed by Dunne et al. (2013), and the other was a simplified version of TOPAZ known as BLING (Galbraith et al. 2010). In 2014, the COBALT ecosystem model of Stock, Dunne, and John (2014) was released with MOM5.
- **Diagnostics**: A key emphasis with MOM5 development was diagnostic capabilities, largely based on work in support of CMIP5, in particular in the development of the ESM2M configuration. Additional efforts were made to document the code, with many refinements made to the MOM manual.
- **Australian co-leadership**: A notable additional attribute of MOM5 is the direct and critical role played by Australian scientists and engineers in support of maintaining the code as an open source project on the web (mom-ocean.org), and providing upgrades and bug fixes. These efforts reflect on the long-standing collaborations between US and Australian ocean scientists, with this interaction now playing a role in MOM6 development.

MOM6: the need for a revolution

Each release of MOM, from MOM1 in 1991 to MOM5 in 2012, saw substantial upgrades to the numerical methods, physical parameterizations, computational infrastructure, test cases, and documentation. These upgrades provided clear and important evolutionary advances to the tool, thus reflecting improved understanding of the ocean garnered from theory and observations, and advances in numerical methods and parameterizations within the broader community. Nonetheless, with the release of MOM5, it was clear that the next step in the MOM lineage required a revolution. Most notably, limitations of a quasi-Eulerian vertical coordinate represented a barrier towards addressing questions about ocean climate related to mesoscale eddies, overflows, and interactions between the ocean and ice shelves.

The mesoscale eddy question raised issues related to spurious diapycnal mixing associated with numerical advection. Griffies et al (2000) identified the problem in idealized tests, and Ilicak et al (2012) provided further evidence for the problem within standard GFDL ocean models based on MOM5. Unfortunately, use of traditional ocean model methods leads to an exacerbation of the problem as the grid is refined sufficiently to allow for transient eddies. One proposal for how to reduce this problem involves the use of isopycnal vertical coordinates, which would represent a radical departure from the familiar level-coordinate approaches used in MOM to date. To accommodate the desire to retain the familiar Eulerian capability and accomplish the transition to Lagrangian methods used in traditional isopycnal models, a general vertical coordinate ability is needed, with this capability delivered by the Arbitrary-Lagrangian-Eulerian method (ALE). ALE methods are fundamentally different from the algorithms built into quasi-Eulerian MOM1-MOM5 models, but naturally mesh with the methods of modern isopycnal model such as GFDL-GOLD (Adcroft and Hallberg 2006).

Downslope gravity flows provide an important conduit for recharging the ocean's densest waters, particularly along the slopes of the Antarctic shelves and through passages such as the Denmark Straits in the North Atlantic. Since the work of Winton, Hallberg, and Gnanadesikan (1998), it has been clear that overflows are particularly tough to simulate in geopotential models, largely due to problems with spurious entrainment as gravity currents flow down slopes. Isopycnal models, in contrast, perform much better (Legg, Hallberg, Girton, 2006, and Wang, Legg, Hallberg 2015), prompting an expectation that isopycnal-like coordinates near the bottom provide a useful strategy for simulating overflows.

Interactions between ice shelves and ocean sit at the heart of the 21st century sea level question. Warming ocean waters pose the most likely means for significant break-up of land ice through collapse of ice shelves. Providing an ocean model tool able to alter its land-sea boundary allows for interactive studies of moving ice shelf grounding lines. A key constraint on such ``wetting and drying'' algorithms is that they offer a perfectly mass conserving capability necessary for long-term climate simulations. No ocean climate model has this capability, except for the GFDL-GOLD (Generalized Ocean Layer Dynamics) code used in the idealized process studies of Goldberg et al (2012a, 2012b). ALE technology again provides a suitable numerical framework for mass conserving wetting-and-drying methods.

The mesoscale eddy problem, overflow problem, and the ice-shelf / ocean problem represent three critical areas of ocean climate science where sophisticated, flexible, and transparent numerical model tools are essential. A group of GFDL ocean scientists, Hallberg, Adcroft, and Griffies, thus decided in 2012 to initiate the MOM6 Project, aiming to bring about a revolution in GFDL ocean climate modeling for use in the 21st century. Since inception, many other at GFDL have contributed to MOM6 development including Whit Anderson, Matthew Harrison, Zhi Liang, Niki Zadeh, John Krasting, Sonya Legg and Tony Rosati.

GFDL-GOLD and isopycnal modeling

The General Ocean Layer Dynamics (GOLD) was developed by Hallberg and Adcroft and collaborators over the years 2004-2012. It was an exploration into use of Lagrangian vertical coordinates, including the ALE method. GOLD had its origins in the Hallberg Isopycnal Model (HIM), first released in 2002, with HIM origins dating back to Hallberg's thesis in 1995 completed under the supervision of Peter Rhines at the University of Washington. The ALE method was originally explored at GFDL using a version of GOLD (White and Adcroft 2008, and White, Adcroft, and Hallberg 2009), taking inspiration from the pioneering work of Rainer Bleck with HyCOM (Bleck, 2002). Furthermore, GOLD was, and remains, a highly sophisticated and successful layered isopycnal model. In particular, it was used in the second earth system model submitted by GFDL to CMIP5 (ESM2G; Dunne et al., 2012). GOLD was publically released in 2012 and immediately frozen, after which time work began on MOM6.

Elements of MOM6 as of 2015

MOM6 as a code base originates from GOLD, building in the needs of a fully generalized vertical coordinate using ALE and generalized physics and diagnostic packages. Here are some of the characteristics of MOM6, with many of these features present in the existing MOM6 code, whereas other features remain aspirational.

- **ALE**: The vertical layering of seawater is based on the ALE method (Bleck 2002), with particular enhancements following the work of White and Adcroft (2008) and White, Adcroft, and Hallberg (2009). The MOM6 formulation of ALE allows for a fully generalized treatment of vertical remapping, offering options for a depth-like, potential density-like, terrain-like, or fully hybrid vertical coordinates.
- **Thin/vanishing layers and wetting/drying:** A key advantage of ALE is that the vertical CFL limitation is removed, thus greatly improving model stability and allowing for arbitrarily thin or vanishing coordinate layers. MOM6 thus has the ability to simulate wetting of formerly dry areas and drying of areas initially ocean, while maintaining conservation of mass to within computational truncation. Such conservative wetting and drying features are essential for a fully interactive climate simulation of sub-ice-shelf cavities, including moving grounding lines as studied using GFDL-GOLD by Goldberg et al (2012a, 2012b).
- **C-Grid:** The horizontal grid is a C-grid rather than the B-grid used in earlier MOM versions. The C-grid is thought to produce more faithful simulation features as the grid resolution is refined to allow for transient mesoscale eddies. C-grid layouts also more accurately represent the land/sea boundaries including choke points. It is notable that virtually all structured community ocean climate models are now based on the C-grid horizontal stencil (e.g., MOM6, MITgcm, HyCOM, ROMS, NEMO).
- **Topography**: Topography generation code has been greatly improved to reduce the degree of subjective decisions. Furthermore, plans are to represent topography via the porous barrier approach detailed in Adcroft (2013).
- **Barotropic time stepping:** The depth integrated equations, approximating the barotropic mode, are time stepped using a split-explicit method, with care taken to ensure consistency between the sea level and the sum of the thicknesses of coordinate layers (Hallberg and Adcroft 2009).
- **Pressure gradient force:** The pressure gradient force is discretized using a finite volume method as described in Adcroft, Hallberg, and Harrison (2008). This method offers a means to reduce errors from spurious pressure gradients occurring with sloped coordinate surfaces in generalized layer models.
- **Equation of state:** The equation of state for seawater is realistic, with care taken to avoid numerical instabilities that can occur in layer models associated with thermobaricity (Hallberg 2005). Plans are to implement an option for the TEOS10 thermodynamics late 2015 or early 2016.
- **Diapycnal mixing parameterizations:** Physical parameterizations of diapycnal mixing in MOM6 include elements of those used in MOM5 as well as GOLD. Notably, the planetary boundary layer schemes will be implemented via the Community Vertical Mixing package

(CVMix), which offers updated versions of KPP (Large et al, 1994), as well as other parameterizations related to breaking gravity waves actively being developed as part of the Internal Gravity Wave Climate Process Team (e.g., Melet et al., 2013, 2015). CVMix also will include a version of an energy-based boundary layer scheme inspired by the bulk mixed layer scheme used in GOLD (Hallberg in prep).

- **Mesoscale eddy parameterizations:** Parameterizations of mesoscale eddies used in MOM6 follow the mesoscale eddy kinetic energy methods of Marshall and Adcroft (2010); the resolution function of Hallberg (2013); and the energy backscatter scheme of Jansen et al. (2015).
- **Submesoscale eddy parameterizations:** Algorithmic updates have been made to the submesoscale parameterization of Fox-Kemper et al. (2008, 2011), rendering the MOM6 implementation more true to the theory set forth in Fox-Kemper et al. (2008).
- **Horizontal friction:** Horizontal frictional dissipation is provided by either Laplacian or biharmonic operators added to the momentum equations. A common choice for viscosity is that suggested by Smagorinsky (1963) for the Laplacian operator, or extended by Griffies and Hallberg (2000) to the biharmonic operator.
- **Diagnostics**: We are initially targeting diagnostic features in MOM6 for the requirements of CMIP6, including full term-balance capabilities for the tracer and momentum equations. Significant further diagnostics are available as per those inherited from GOLD, and these are actively being generalized to generalized ALE vertical coordinates.
- **Test cases:** There are numerous test cases provided with MOM6, from idealized to realistic. These model configurations are continually being tested as code is modified to ensure that any answer changes are fully documented.
- **Documentation for running MOM6**: Documentation for running MOM6 simulations is available on the MOM6 GitHub site, with refinements being made to clarify the many technical points.
- **Documentation for setting up new MOM6 configurations:** Documentation for how to configure new MOM6 models remains an ongoing task.
- **Documentation of MOM6 theory and numerics:** There is no grand “MOM6 Manual” to compare to those available with earlier MOM versions. Such remains a project for the coming years.

SIS2

Although this document is focused on MOM, we briefly mention efforts related to sea ice modeling. Version 2 of the Sea Ice Simulator (SIS2) has been developed at GFDL by Hallberg and Mike Winton. SIS2 is a C-grid ice model (SIS1 is B-grid) that shares many of the same numerical and computational features of MOM6. Thermodynamics in SIS2 follow that of SIS1, but with important additional features taken from the Los Alamos CICE code. Further development of SIS2 is planned so that the sea ice dynamics will be embedded within the ocean model, so that the external modes for both the sea ice and ocean are solved together. Doing so eliminates several numerical instabilities common with current coupled ocean-ice models, particularly those with fine horizontal resolution.

Open Source Development

MOM6 and SIS2 are available using an open-development software model – meaning that ongoing development of the code within GFDL is visible to collaborators and the public. Presently, the model remains under active development, with code changes made almost daily. More thorough support for outside use will begin with the first formal release of MOM6. This release will represent a state of completion for the first phase of development. We are targeting this release with completion of GFDL's CMIP6 earth system model, CM4, expected in 2016.

Summary and closing comments

The ocean models developed at GFDL have been very successful for science and operational applications for the past 50+ years. Indeed, they have defined the state-of-the-science for much of that time. When Mike Cox made the Bryan-Cox code public in 1984, he set a precedent for openness of software allowing the rest of the ocean and climate community to take advantage of GFDL's active modeling efforts. After Mike Cox's passing in 1989, others at GFDL followed his lead. They have greatly improved the code, test cases, and user manuals, thus allowing for an increased number of scientists to benefit from and contribute to the MOM community. GFDL has in turn benefited from the strong community interactions and collaborations. In particular, many new parameterizations and numerical methods were imported into the code based on community input. Furthermore, many fundamental insights into oceanography and climate have been facilitated by use of the code within the broader science community. The public releases of each MOM version have thus supported a growing intellectual base for oceanography, with numerical models a key tool for providing a mechanistic understanding of the ocean.

With development of MOM6, we expect continued success of GFDL's ocean modeling efforts. Many novel features found in MOM6 will attract the attention of ocean model developers and users alike. These features are designed in particular to solve certain limitations found in today's ocean model simulations. Hence, we trust that MOM6 will have a significant impact on oceanography and climate science worldwide.

Acknowledgments

This document summarizes more than 50 years of research and development related to MOM. Rather than thank the numerous individuals having influenced this history, we wish to acknowledge the very special environment at GFDL that continues to allow its scientists and engineers to address the huge research and development tasks related to climate modeling. These tasks generally require decades, and can span generations of scientists and engineers. We thank the scientist managers whose vision and resolve fostered this environment ever since the founding of GFDL in 1955.

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