Elements of MOM4p1

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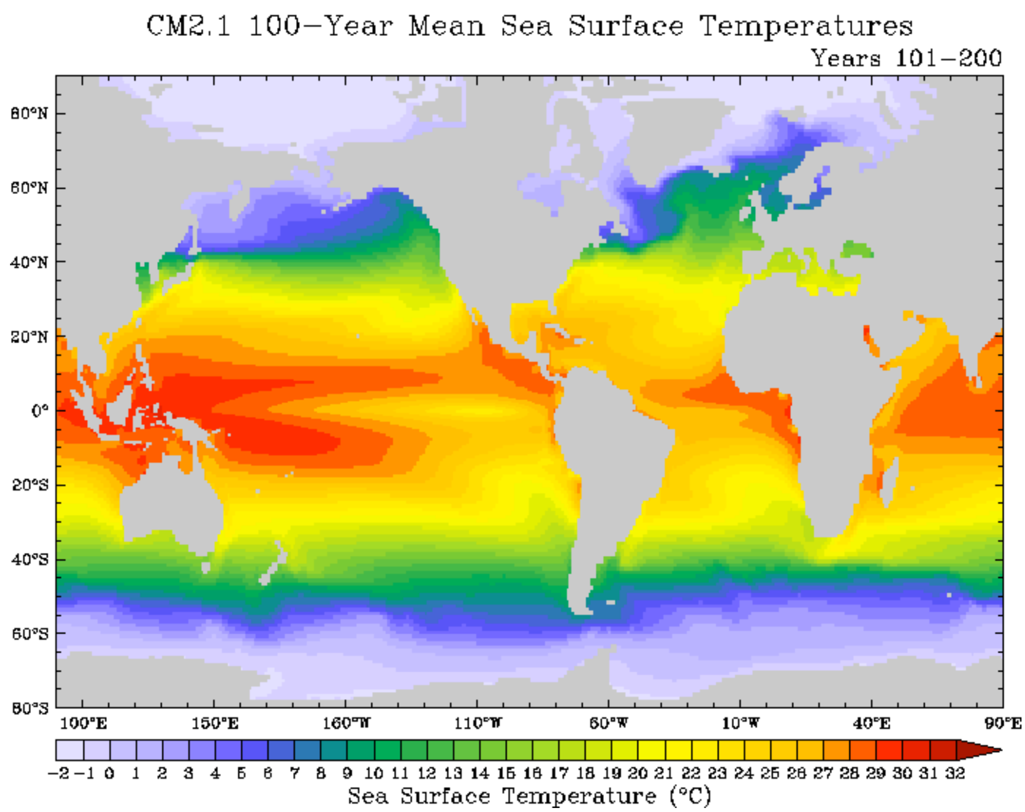

This document is freely distributed for ocean scientists interested in understanding the fundamentals of version 4.1 of the Modular Ocean Model (MOM). This document should be referenced as

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Code and documentation available online at `www.gfdl.noaa.gov/fms`.

Information about how to download and run MOM4 can be found at the GFDL Flexible Modeling System (FMS) web site accessible from `www.gfdl.noaa.gov/fms`.

CONTENTS

CHAPTER

ONE

Executive summary of MOM4p1

MOM4p1 is a B-grid hydrostatic nonBoussinesq ocean model, with a Boussinesq option. This chapter provides an itemized summary of various code features. More discussion is provided in subsequent chapters. Note that items written in small capitals are new or substantially updated relative to MOM4.0.

1.1 General features

- GENERALIZED DEPTH AND PRESSURE BASED LEVEL VERTICAL COORDINATES.
  - Full support for the quasi-horizontal coordinates

$$
\begin{aligned}
s &= z \\
s &= z^* = H\left(\frac{z-\eta}{H+\eta}\right) \\
s &= p \\
s &= p^* = p^o_{\mathrm{b}}\left(\frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}\right)
\end{aligned}
$$

  - Partial support for the terrain following coordinates

$$
\begin{aligned}
s &= \sigma^{(z)} = \frac{z-\eta}{H+\eta} \\
s &= \sigma^{(p)} = \frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}
\end{aligned}
$$

    There is presently no support for terrain following coordinates using neutral physics, KPP vertical mixing, nor for sophisticated horizontal pressure gradient algorithms.

- Generalized orthogonal horizontal coordinates, with the tripolar grid of Murray (1996) supported in test cases. Other orthogonal grids have been successfully employed with MOM4.

- Parallel programming: MOM4p1 follows the parallel programming approach of MOM4.0, and is written with arrays ordered `(i,j,k)` for straightforward processor domain decomposition. As with MOM4.0, MOM4p1 relies on the GFDL Flexible Modeling System (FMS) (`http://www.gfdl.noaa.gov/fms`) infrastructure and superstructure code for computations on multiple parallel machines, with the code having been successfully run on dozens of computer platforms.

- EXPLICIT FREE SURFACE AND EXPLICIT BOTTOM PRESSURE SOLVER: MOM4 employs a split-explicit time stepping scheme where fast two-dimensional dynamics is sub-cycled within the slower three dimensional dynamics. The method follows ideas detailed in Chapter 12 of Griffies (2004), which are based on Killworth et al. (1991) and Griffies et al. (2001). Chapter 7 in this document presents further details for MOM4p1.

- Time stepping schemes: The time tendency for tracer and baroclinic velocity can be discretized two ways.

  - The first approach uses the traditional leap-frog method for the dissipation-less portion of the dynamics, along with a Robert-Asselin time filter (Haltiner and Williams, 1980). This method is retained solely for legacy purposes. It is *not* reccomended for general use.
  - The preferred time steppng method discretizes the time tendency with a two-level forward step, which eliminates the time splitting mode and so eliminates the need for a Robert-Asselin time filter. Tracer and velocity are staggered in time, thus providing, ideally, a second order time accurate method. For certain model configurations, this scheme has been found to be twice as efficient as the leap-frog based scheme since one can take twice the time step with the two-level approach (e.g., the global climate model test case presented in Chapter 37). Furthermore, without the time filtering needed with the leap-frog, the new scheme conserves total tracer to within numerical roundoff. This scheme is discussed in Griffies (2004), Griffies et al. (2005), and in Chapter 7 of this document.

- EQUATION OF STATE: The equation of state in MOM4p1 follows the formulation of Jackett et al. (2006), where the coefficients from McDougall et al. (2003) are updated to new empirical data.

- UPDATED FREEZING TEMPERATURE FOR FRAZIL: Accurate methods for computing the freezing temperature of seawater are provided by Jackett et al. (2006). These methods allow, in particular, for the computation of the freezing point at arbitrary depth, which is important for ice shelf modelling.

- CONSERVATIVE TEMPERATURE: MOM4p1 time steps the conservative temperature described by McDougall (2003) to provide a measure of heat in the ocean (see Section 3.3.2). This variable is about 100 times more conservative than the traditional potential temperature variable. An option exists to set either conservative temperature or potential temperature prognostic, with the alternative temperature variable carried as a diagnostic tracer.

- PRESSURE GRADIENT CALCULATION: The pressure gradient calculation has been updated in MOM4p1 to allow for the use of generalized level coordinates. A description of the formulation is given in Chapter 4. None of the sophisticated methods described by Shchepetkin and McWilliams (2002) are implemented in MOM4p1, and so terrain following vertical coordinates may suffer from unacceptably large pressure gradients errors in MOM4p1.

- Partial bottom steps: MOM4p1 employs the partial bottom step technology of Pacanowski and Gnanadesikan (1998) to facilitate the representation of bottom topography. This approach is implemented for all of the vertical coordinates.

- TRACER ADVECTION: MOM4p1 comes with the following array of tracer advection schemes. Note that centred schemes are stable *only* for the leap-frog version of MOM4p1. We thus partition the advection schemes according to the corresponding time stepping schemes.

  – Schemes available for either time stepping method

    1. First order upwind
    2. Quicker scheme is third order upwind biased and based on the Leonard (1979). Holland et al. (1998) and Pacanowski and Griffies (1999) discuss implementations in ocean climate models. This scheme does not have flux limiters, so it is not monotonic.
    3. Quicker-MOM3: The Quicker scheme in MOM4p1 differs slightly from that in MOM3, and so the MOM3 algorithm has also been ported to MOM4p1.
    4. Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with Super-B flux limiters.
    5. Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with flux limiters of Sweby (1984).
    6. The second moment scheme of Prather (1986) has been implemented in MOM4p1. It is available without limiters, or with the limiters of Merryfield and Holloway (2003).
    7. The piece-wise parabolic method has been implemented in MOM4p1.

  – Schemes available only for leap-frog time stepping

    1. Second order centred differences
    2. Fourth order centred differences: This scheme assumes the grid is uniformly spaced (in metres), and so is less than fourth order accurate when the grid is stretched, in either the horizontal or vertical.
    3. Sixth order centred differences: This scheme assumes the grid is uniformly spaced (in metres), and so is less than sixth order accurate when the grid is stretched, in either the horizontal or vertical. This scheme is experimental, and so *not* supported for general use.

- TRACER PACKAGES: MOM4p1 comes with an array of tracer packages of use for understanding water mass properties and for building more sophisticated tracer capabilities, such as for ocean ecosystem models. These packages include the following.

  - Idealized passive tracer module with internally generated initial conditions. These tracers are ideal for testing various advection schemes, for example, as well as to diagnose pathways of transport.
  - An ideal age tracer, with various options for specifying the initial and boundary conditions.
  - The OCMIP2 protocol tracers (CO_2, CFC, biotic).
  - iBGC: An intermediate complexity ocean biogeochemistry model.
  - BLING: Another ocean biogeochemistry model. This model has been written in a *generic* format to allow for its use with both MOM4p1 and GFDL's isopycnal model GOLD.
  - TOPAZ: A comprehensive model of oceanic ecosystems and biogeochemical cycles is a state of the art model that considers 22 tracers including three phytoplankton groups, two forms of dissolved organic matter, heterotrophic biomass, and dissolved inorganic species for C, N, P, Si, Fe, $CaCO_3$ and O_2 cycling. The model includes such processes as gas exchange, atmospheric deposition, scavenging, N_2 fixation and water column and sediment denitrification, and runoff of C, N, Fe, O_2, alkalinity and lithogenic material. The phytoplankton functional groups undergo co-limitation by light, nitrogen, phosphorus and iron with flexible physiology. Loss of phytoplankton is parameterized through the size-based relationship of Dunne et al. (2005). Particle export is described through size and temperature based detritus formation and mineral protection during sinking with a mechanistic, solubility-based representation alkalinity addition from rivers, $CaCO_3$ sedimentation and sediment preservation and dissolution. This model has been written in a *generic* format to allow for its use with both MOM4p1 and GFDL's isopycnal model GOLD.

- Penetration of shortwave radiation as discussed in Sweeney et al. (2005) using various attenuation options.

- Horizontal friction: MOM4p1 has a suite of horizontal friction schemes, such as Smagorinsky laplacian and biharmonic schemes described in Griffies and Hallberg (2000) and the anisotropic laplacian scheme from Large et al. (2001) and Smith and McWilliams (2003).

- Convection: There are various convective methods available for producing a gravitationally stable column. The scheme used most frequently at GFDL for certain idealized studies is that due to Rahmstorf (1993).

- NEUTRAL PHYSICS AND BOUNDARY REGIONS: There are new options available for treating neutral physics within boundary regions, as motivated from ideas proposed by Ferrari et al. (2008). The MOM4p1 formulation is given in Chapter 16

- FORM DRAG: MOM4p1 has various options associated with the parameterization of form drag arising from unresolved mesoscale eddies, as proposed by Greatbatch and Lamb (1990), Aiki et al. (2004), and Ferreira and Marshall (2006).

- RESTRATIFICATION EFFECTS FROM SUBMESOSCALE EDDIES: There is a new option available for parameterizing the restratification effects from submesoscale eddies, as proposed by Fox-Kemper et al. (2008b). The MOM4p1 formulation is given in Chapter 18.

- TIDAL MIXING PARAMETERIZATION: The Simmons et al. (2004) parameterization has been implemented as a means to parameterize the diapycnal mixing effects from breaking internal gravity waves, especially those waves influenced by rough bottom topography. Additionally, this scheme has been combined with that used by Lee et al. (2006), who discuss the importance of barotropic tidal energy on shelves for dissipating energy and producing tracer mixing. Chapter 14 presents the MOM4p1 formulation.

- Other vertical mixing schemes: MOM4p1 comes with an array of vertical mixing schemes, such as the following.

  – Constant background diffusivity proposed by Bryan and Lewis (1979).
  – The Pacanowski and Philander (1981) Richardson number dependent scheme.
  – The KPP scheme of Large et al. (1994).
  – GENERAL OCEAN TURBULENCE MODEL (GOTM): MOM4p1 has a wrapper enabling a 3d general circulation simulation to employ the one-dimensional physics closures available from (Umlauf et al., 2005).

- UPDATE OF OVERFLOW SCHEMES: MOM4p1 comes with various methods of use for parameterizing, or at least facilitating the representation of, dense water moving into the abyss. These schemes are documented in Chapter 19.

- REFINED OPEN BOUNDARY CONDITIONS MODULE: The open boundary conditions module has been updated for MOM4p1 to facilitate its use for regional modelling as described by Herzfeld et al. (2010). Chapter 12 presents some details. This scheme has been developed for use only with depth based vertical coordinates, with z and z^* the two coordinates that have been tested. No development has been given to pressure based vertical coordinates. Pressure based coordinates solve for the bottom pressure rather than the surface height. Hence, there are algorithm development issues required to extend the present OBC code to handle pressure based vertical coordinates.

- UPDATED SPURIOUS MIXING DIAGNOSTIC: Griffies et al. (2000b) describe an empirical diagnostic method to diagnose the levels of mixing occurring in a model. This diagnostic required some upgrades to allow for the use of thickness weighting for time stepping the prognostic fields. This diagnostic is described in Chapter 23. Also, the method of Burchard and Rennau (2008) is available in MOM4p1 to diagnose the dissipation associated with numerical advection. Details of the MOM4p1 implementation of this diagnostic are provided in Chapter 24.

- STERIC SEA LEVEL DIAGNOSTIC: We provide some added diagnostics for understanding how sea level evolves. Preliminary formulation is given in Chapter 26.

- REVISED TEST CASES: All of the test cases have been revised as well as the addition of some new tests. Documentation of these tests is presented in Part V of this document.

- UPDATED FMS INFRASTRUCTURE AND PREPROCESSING TOOLS: As with all releases of mom4, it comes with updated infrastructure, preprocessing code, coupling code, etc. supported by an array of scientists and engineers at GFDL.

1.2 Relating MOM4p1 to MOM4.0

- Backward compatibility

  There is *no option* that will provide bitwise agreement between MOM4p1 simulations and MOM4.0 simualations. Providing this feature was deemed too onerous on the development of MOM4p1, in which case many of the algorithms were rewritten, reorganized, and modified.

  Nonetheless, some features have been preserved, with the aim to provide a reasonable path towards backward checking. In particular, the mom4p0 neutral physics algorithm has been retained, and indeed is recommended for production runs. Additionally, changes to KPP mentioned below are provided in the MOM4p1 version of this module, with the MOM4.0 version ported to MOM4p1 for legacy purposes.

- Bug fixes

  1. The shortwave penetration module in MOM4.0 failed to account for the undulating surface height when computing the attenuation of shortwave entering the ocean. For many cases this bug is of minor consequence. But when refining the vertical resolution, the surface height undulations must be accounted for when attentuating shortwave. Additionally, for general vertical coordinates, undulating depths are the norm, so the shortwave algorithm needed to be updated.
  2. The KPP vertical mixing scheme included many places where the vertical grid was assumed to be rigid and one dimensional. As for the shortwave, this code was originally developed for a rigid lid z-model. When generalizing to free surface, partial bottom steps, and vertical coordinates, the vertical grid becomes a dynamic three dimensional array, which required some modifications to the code.

- General cleanup and additions

  1. Numerous additional diagnostic features;
  2. Basic code clean up with bit more tidy code style in most places;
  3. Thoroughly updated documentation of MOM4p1 as a complement to the MOM4 Technical Guide of Griffies et al. (2004).

CHAPTER
TWO

Synopsis of MOM4p1

The purpose of this document is to detail the formulation, methods, and selected SGS parameterizations of MOM4p1. This document complements many of the discussions in the MOM3 Manual of Pacanowski and Griffies (1999), the MOM4 Technical Guide of Griffies et al. (2004), and the monograph by Griffies (2004).

The equations and methods of MOM4p1 are based on the hydrostatic and nonBoussinesq equations of the ocean along with a selection of subgrid scale (SGS) parameterizations. The model is written with rudimentary general level coordinate capabilities employing a quasi-Eulerian algorithm. Notably, this approach precludes it from running as a traditional isopycnal layered model, which generally use quasi-Lagrangian algorithms. Nonetheless, the generalized level coordinate features of MOM4p1 distinguish it most noticeably from MOM4.0. The purpose of this chapter is to summarize the basic elements of MOM4p1. Features new relative to MOM4.0 are highlighted in smallcaps.

2.1 What is MOM?

The Modular Ocean Model (MOM) is a numerical representation of the ocean's hydrostatic primitive equations. It is designed primarily as a tool for studying the ocean climate system. Additionally, MOM has been used in regional and coastal applications, with many new features in MOM4p1 aimed at supporting this work. The model is developed by researchers from around the world, with the main algorithm development and software engineering provided by NOAA's Geophysical Fluid Dynamics Laboratory (GFDL). The model is freely available via

`http://www.gfdl.noaa.gov/fms`

MOM evolved from numerical ocean models developed in the 1960's-1980's by Kirk Bryan and Mike Cox at GFDL. Most notably, the first internationally released and supported primitive equation ocean model was developed by Mike Cox (Cox (1984)). It cannot be emphasized enough how revolutionary it was in 1984 to freely release, support, and document code for use in numerical ocean climate modeling. The Cox-code provided scientists worldwide with a powerful tool to investigate basic and applied questions about the ocean and its interactions with other components of the climate system. Previously, rational investigations of such questions by most scientists were limited to restrictive idealized models and analytical methods. Quite simply, the Cox-code started what has today become a right-of-passage for every high-end numerical model of dynamical earth systems.

Upon the untimely passing of Mike Cox in 1990, Ron Pacanowski, Keith Dixon, and Tony Rosati rewrote the Cox code with an eye on new ideas of modular programming using Fortran 77. The result was the first version of MOM (Pacanowski et al. (1991)). Version 2 of MOM (Pacanowski (1995)) introduced the memory window idea, which was a generalization of the vertical-longitudinal slab approach used in the Cox-code and MOM1. Both of these methods were driven by the desires of modelers to run large experiments on machines with relatively small memories. The memory window provided enhanced flexibility to incorporate higher order numerics, whereas slabs used in the Cox-code and MOM1 restricted the numerics to second order. MOM3 (Pacanowski and Griffies (1999)) even more fully exploited the memory window with a substantial number of physics and numerics options.

The Cox-code and each version of MOM came with a manual. Besides describing the elements of the code, these manuals aimed to provide transparency to the rationale underlying the model's numerics. Without such, the model could in many ways present itself as a black box, thus greatly hindering its utility to the scientific researcher. This philosophy of documentation saw its most significant realization in the MOM3 Manual, which reaches to 680 pages. The present document is written with this philosophy in mind, yet allows itself to rely somewhat on details provided in the previous manuals as well as theoretical discussions given by Griffies (2004).

The most recent version of MOM is version 4. The origins of MOM4 date back to a transition from vector to parallel computers at GFDL, starting in 1999. Other models successfully made the transition some years earlier (e.g., The Los Alamos Parallel Ocean Program (POP) and the OCCAM model from Southampton, UK). New computer architectures generally allow far more memory than previously available, thus removing many of the reasons for the slabs and memory window approaches used in earlier versions of MOM. Hence, we concluded that the memory window should be jettisoned in favor of a straightforward horizontal 2D domain decomposition. Thus began the project to redesign MOM for use on parallel machines.

2.2 First release of MOM4.0: October 2003

When physical scientists aim to rewrite code based on software engineering motivations, more than software issues are addressed. During the writing of MOM4, numerous algorithmic issues were also addressed, which added to the development time. Hence, the task of rewriting MOM3 into MOM4.0 took roughly four years to complete.

2.3 First release of MOM4p1: Early 2007

Griffies spent much of 2005 in Hobart, Australia as a NOAA representative at the CSIRO Marine and Atmospheric Research Laboratory, as well as with researchers at the University of Tasmania. This period saw focused work to upgrade MOM4 to include certain features of generalized level coordinates. An outline of these, and other features, is given in the following sections.

By allowing for the use of a suite of vertical coordinates, MOM4p1 is algorithmically more flexible than any previous version of MOM. This work, however, did not fundamentally alter the overall computational structure relative to the last release of MOM4.0 (the MOM4p0d release in

May 2005). In particular, MOM4p1 is closer in "look and feel" to MOM4p0d than MOM4p0a is to MOM3.1. Given this similarity, it was decided to retain the MOM4 name for the MOM4p1 release, rather switch to MOM5. Many of the newer features in MOM4p1 should be considered experimental, and worthy of use mainly for research purposes.

2.4 MOM4p1 release May 2009

The MOM4p1 release of May 2009 represents a major upgrade to the code, especially those areas related to the open boundary conditions (Chapter 12 and Herzfeld et al. (2010)), various physical parameterizations, diagnostics, and FMS infrastructure. This public release also provides the community with a *test case* consisting of the CM2.1 configuration used by GFDL for the IPCC AR4 assessment, as documented by Griffies et al. (2005), Gnanadesikan et al. (2006a), Delworth et al. (2006), Wittenberg et al. (2006), and Stouffer et al. (2006). Although CM2.1 for the AR4 assessement actually used MOM4.0, the setup in the CM2.1-MOM4p1 test case is backwards compatibile.

2.5 Fundamentals of MOM4p1

In this section, we outline fundamental features of MOM4p1; that is, features that are always employed when using the code.

- GENERALIZED LEVEL COORDINATES: Various vertical coordinates have been implemented in MOM4p1. We have focused attention on vertical coordinates based on functions of depth or pressure, which means in particualar that MOM4p1 *does not* support thermodynamic or isopycnal based vertical coordinates.[1]

  The following list summarizes vertical coordinates presently implemented in MOM4p1. Extensions to other vertical coordinates are straightforward, given the framework available for the coordinates already present. Full details of the vertical coordinates are provided in Chapter 6.

  - Geopotential coordinate as in MOM4.0, including the undulating free surface at $z = \eta$ and bottom partial cells approximating the bottom topography at $z = -H$

    $$s = z. \tag{2.1}$$

  - Quasi-horizontal rescaled height coordinate of Stacey et al. (1995) and Adcroft and Campin (2004)

    $$\begin{aligned} s &= z^* \\ &= H\left(\frac{z-\eta}{H+\eta}\right). \end{aligned} \tag{2.2}$$

[1]The Hallberg Isopycnal Model (HIM) is available from GFDL for those wishing to use layered models. HIM is a Fortran code that is fully supported by GFDL scientists and engineers. Information about HIM is available at `http://www.gfdl.noaa.gov/fms/`.

– Depth based terrain following "sigma" coordinate, popular for coastal applications

$$\begin{aligned} s &= \sigma^{(z)} \\ &= \frac{z - \eta}{H + \eta}. \end{aligned} \tag{2.3}$$

– Pressure coordinate

$$s = p \tag{2.4}$$

was shown by Huang et al. (2001), DeSzoeke and Samelson (2002), Marshall et al. (2004), and Losch et al. (2004) to be a useful way to transform Boussinesq z-coordinate models into nonBoussinesq pressure coordinate models.

– Quasi-horizontal rescaled pressure coordinate

$$\begin{aligned} s &= p^{*} \\ &= p_{\mathrm{b}}^{o} \left(\frac{p - p_{\mathrm{a}}}{p_{\mathrm{b}} - p_{\mathrm{a}}} \right), \end{aligned} \tag{2.5}$$

where p_{a} is the pressure applied at the ocean surface from the atmosphere and/or sea ice, p_{b} is the hydrostatic pressure at the ocean bottom, and p_{b}^{o} is a time independent reference bottom pressure.

– Pressure based terrain following coordinate

$$\begin{aligned} s &= \sigma^{(p)} \\ &= \left(\frac{p - p_{\mathrm{a}}}{p_{\mathrm{b}} - p_{\mathrm{a}}} \right). \end{aligned} \tag{2.6}$$

Note the following points:

– All depth based vertical coordinates implement the volume conserving, Boussinesq, ocean primitive equations.

– All pressure based vertical coordinates implement the mass conserving, nonBoussinesq, ocean primitive equations.

– There has little effort focused on reducing pressure gradient errors in the terrain following coordinates (Section 4.2). Researchers intent on using terrain following coordinates may find it necessary to implement one of the more sophisticated pressure gradient algorithms available in the literature, such as that from Shchepetkin and McWilliams (2002).

– Use of neutral physics parameterizations (Section 5.2.3 and Chapter 16) with terrain following coordinates is not recommended with the present implementation. There are formulation issues that have not been addressed, since the main focus of neutral physics applications at GFDL centres on vertical coordinates that are quasi-horizontal.

– Most of the vertical coordinate dependent code is in the

`mom4/ocean_core/ocean_thickness`

module, where the thickness of a grid cell is updated according to the vertical coordinate choice. The developer intent on introducing a new vertical coordinate may find it suitable to emulate the steps taken in this module for other vertical coordinates. The remainder of the model code is generally transparent to the specific choice of vertical coordinate, and such has facilitated a straightforward upgrade of the code from MOM4.0 to MOM4p1.

- Generalized orthogonal horizontal coordinates: MOM4p1 is written using generalized horizontal coordinates, with the coordinates assumed to be locally orthogonal. The formulation in this document follows this approach as well. For global ocean climate modelling, MOM4p1 comes with test cases (the OM3 test case in Chapter 37) using the tripolar grid of Murray (1996). Other orthogonal grids have been successfully employed with MOM4.0.

  Code for reading in the grid and defining MOM4 specific grid factors is found in the module

  `mom4/ocean_core/ocean_grids`.

  MOM comes with preprocessing code suitable for generating grid specification files of various complexity, including the Murray (1996) tripolar grid. Note that the horizontal grid in MOM4 is static (time independent), whereas the vertical grid is generally time dependent. Hence, there is utility in separating the horizontal from the vertical grids.

- Parallel programming: MOM4p1 follows the parallel programming approach of MOM4.0, and is written with arrays ordered `(i,j,k)` for straightforward processor domain decomposition.

- Explicit free surface and explicit bottom pressure solver: MOM4 employs a split-explicit time stepping scheme where fast two-dimensional dynamics is sub-cycled within the slower three dimensional dynamics. The method follows ideas detailed in Chapter 12 of Griffies (2004), which are based on Killworth et al. (1991) and Griffies et al. (2001). Chapter 7 presents the details for MOM4p1, and the code is on the module

  `mom4/ocean_core/ocean_barotropic`.

- Time stepping schemes: The time tendency for tracer and baroclinic velocity can be discretized two ways.

  1. The first approach uses the traditional leap-frog method for the inviscid/dissipationless portion of the dynamics, along with a Robert-Asselin time filter.
  2. The preferred method discretizes the time tendency with a two-level forward step, which eliminates the need to time filter. Tracer and velocity are staggered in time, thus providing second order accuracy in time. For certain model configurations, this scheme has been found to be twice as efficient as the leap-frog based scheme since one can take twice the time step with the two-level approach. Furthermore, without the time filtering needed with the leap-frog, the new scheme conserves total tracer to within numerical roundoff. This scheme is discussed in Griffies et al. (2005) and Griffies (2004) (see Chapter 12), as well as in Chapter 7 of this document.

The code implementing these ideas in MOM4p1 can be found in

mom4/ocean_core/ocean_velocity
mom4/ocean_tracers/ocean_tracer

- Time stepping the Coriolis force: As discussed in Chapter 11, there are various methods available for time stepping the Coriolis force on the B-grid used in MOM4. The most commonly used method for global climate simulations at GFDL is the semi-implicit approach in which half the force is evaluated at the present time and half at the future time.
- EQUATION OF STATE: As discussed in Chapter 9, the equation of state in MOM4p1 follows the formulation of Jackett et al. (2006), where the coefficients from McDougall et al. (2003) are updated to new empirical data. The code for computing density is found in the module

  mom4/ocean_core/ocean_density.

- CONSERVATIVE TEMPERATURE: MOM4p1 time steps the conservative temperature described by McDougall (2003) to provide a measure of heat in the ocean (see Section 3.3.2). This variable is about 100 times more conservative than the traditional potential temperature variable. An option exists to set either conservative temperature or potential temperature prognostic, with the alternative temperature variable carried as a diagnostic tracer. This code for computing conservative temperature is within the module

  mom4/ocean_tracers/ocean_tempsalt.

- PRESSURE GRADIENT CALCULATION: The pressure gradient calculation has been updated in MOM4p1 to allow for the use of generalized vertical coordinates. A description of the formulation is given in Chapter 4, and the code is in the module

  mom4/ocean_core/ocean_pressure.

  Notably, none of the sophisticated methods described by Shchepetkin and McWilliams (2002) are implemented in MOM4p1, and so terrain following vertical coordinates may suffer from unacceptably large pressure gradients errors in MOM4p1. Researchers are advised to perform careful tests prior to using these coordinates.

- Partial bottom steps: MOM4p1 employs the partial bottom step technology of Pacanowski and Gnanadesikan (1998) to facilitate the representation of bottom topography, with the code in the module

  mom4/ocean_core/ocean_topog.

2.6 Tracer features

Here, we outline some of the features available for tracers in MOM4p1.

- TRACER ADVECTION: MOM4p1 comes with the following array of tracer advection schemes. Note that centred schemes are stable *only* for the leap-frog version of MOM4p1. We thus partition the advection schemes according to the corresponding time stepping schemes. The code for tracer advection schemes are in the module

  `mom4/ocean_tracers/ocean_tracer_advect`.

  – Schemes available for either time stepping method
    1. First order upwind
    2. Quicker scheme is third order upwind biased and based on the Leonard (1979). Holland et al. (1998) and Pacanowski and Griffies (1999) discuss implementations in ocean climate models. This scheme does not have flux limiters, so it is not monotonic.
    3. Quicker-MOM3: The Quicker scheme in MOM4p1 differs slightly from that in MOM3, and so the MOM3 algorithm has also been ported to MOM4p1.
    4. Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with Super-B flux limiters.[2] The scheme is available in MOM4p1 with either time stepping scheme.
    5. Multi-dimensional third order upwind biased approach of Hundsdorfer and Trompert (1994), with flux limiters of Sweby (1984).[3] It is available in MOM4p1 with either time stepping scheme.
    6. The second moment scheme of Prather (1986) has been implemented in MOM4p1. It is available without limiters, or with the limiters of Merryfield and Holloway (2003).
    7. The piece-wise parabolic method has been implemented in MOM4p1.

    Both of the MIT-based schemes are non-dispersive, preserve shapes in three dimensions, and preclude tracer concentrations from moving outside of their natural ranges in the case of a purely advective process. They are modestly more expensive than the Quicker scheme, and it do not significantly alter the simulation relative to Quicker in those regions where the flow is well resolved. The Sweby limiter code was used for the ocean climate model documented by Griffies et al. (2005).

  – Schemes available only for leap-frog time stepping
    1. Second order centred differences
    2. Fourth order centred differences: This scheme assumes the grid is uniformly spaced (in metres), and so is less than fourth order accurate when the grid is stretched, in either the horizontal or vertical.
    3. Sixth order centred differences: This scheme assumes the grid is uniformly spaced (in metres), and so is less than sixth order accurate when the grid is stretched, in

[2]This scheme was ported to MOM4 by Alistair Adcroft, based on his implementation in the MITgcm. The online documentation of the MITgcm at `http://mitgcm.org` contains useful discussions and details about this advection scheme.

[3]This scheme was ported to MOM4 by Alistair Adcroft, based on his implementation in the MITgcm. The online documentation of the MITgcm at `http://mitgcm.org` contains useful discussions and details about this advection scheme.

either the horizontal or vertical. This scheme is experimental, and so *not* supported for general use.

- TRACER PACKAGES: MOM4p1 comes with an array of tracer packages of use for understanding water mass properties and for building more sophisticated tracer capabilities, such as for ocean ecosystem models. Modules for these tracers are in the directories

  `mom4/ocean_tracers`
  `mom4/ocean_bgc`
  `ocean_shared/generic_tracers`.

  The tracer packages include the following.

  - Idealized passive tracer module with internally generated initial conditions. These tracers are ideal for testing various advection schemes, for example, as well as to diagnose pathways of transport.
  - An ideal age tracer, with various options for specifying the initial and boundary conditions.
  - The OCMIP2 protocol tracers (CO_2, CFC, biotic).
  - iBGC: A simple ocean biogeochemistry model.
  - BLING: An intermediate complexity ocean biogeochemistry model. This model has been written in a *generic* format to allow for its use with both MOM4p1 and GFDL's model code GOLD.
  - TOPAZ: A comprehensive model of oceanic ecosystems and biogeochemical cycles is a state of the art model that considers 22 tracers including three phytoplankton groups, two forms of dissolved organic matter, heterotrophic biomass, and dissolved inorganic species for C, N, P, Si, Fe, $CaCO_3$ and O_2 cycling. The model includes such processes as gas exchange, atmospheric deposition, scavenging, N_2 fixation and water column and sediment denitrification, and runoff of C, N, Fe, O_2, alkalinity and lithogenic material. The phytoplankton functional groups undergo co-limitation by light, nitrogen, phosphorus and iron with flexible physiology. Loss of phytoplankton is parameterized through the size-based relationship of Dunne et al. (2005). Particle export is described through size and temperature based detritus formation and mineral protection during sinking with a mechanistic, solubility-based representation alkalinity addition from rivers, $CaCO_3$ sedimentation and sediment preservation and dissolution. This model has been written in a *generic* format to allow for its use with both MOM4p1 and GFDL's isopycnal model GOLD.

- UPDATED FREEZING TEMPERATURE FOR FRAZIL: Accurate methods for computing the freezing temperature of seawater are provided by Jackett et al. (2006). These methods allow, in particular, for the computation of the freezing point at arbitrary depth, which is important for ice shelf modelling. These methods have been incorporated into the frazil module

  `mom4/ocean_tracers/ocean_frazil`,

  with heating due to frazil formation treated as a diagnostic tracer.

- PENETRATION OF SHORTWAVE RADIATION: The following modules are available for computing shortwave penetration into the ocean

  `mom4/ocean_param/sources/ocean_shortwave`
  `mom4/ocean_param/sources/ocean_shortwave_csiro`
  `mom4/ocean_param/sources/ocean_shortwave_gfdl`
  `mom4/ocean_param/sources/ocean_shortwave_jerlov`

  with the reader referred to each module for full documentation. In brief, these modules provide the following options.

  – `ocean_shortwave`: This module drives the other shortwave modules.
  – `ocean_shortwave_csiro`: This module implements a simple exponential decay for the penetrative shortwave radiation. This module was prepared at CSIRO Marine and Atmospheric Research in Australia.
  – `ocean_shortwave_gfdl`: This module implements the optical model of Morel and Antoine (1994) as well as that of Manizza et al. (2005).
    * Sweeney et al. (2005) compile a seasonal climatology of chlorophyll based on measurements from the NASA SeaWIFS satellite, and this climatology is available with the distribution of MOM4. They used this data to develop two parameterizations of visible light absorption based on the optical models of Morel and Antoine (1994) and Ohlmann (2003). The two models yield quite similar results when used in global ocean-only simulations, with very small differences in heat transport and overturning.
    * The Morel and Antoine (1994) method for attenuating shortwave radiation was employed in the CM2 coupled climate model, as discussed by Griffies et al. (2005). In MOM4p1, we updated the implementation of this algorithm relative to MOM4.0 by including the time dependent nature of the vertical position of a grid cell. The MOM4.0 implementation used the vertical position appropriate only for the case of a static ocean free surface.
    * In more recent model development, especially that associated with interactive biogeochemistry, GFDL modelers have employed the scheme from Manizza et al. (2005) rather than Morel and Antoine (1994).
  – `ocean_shortwave_jerlov`: This module implements yet another exponential decay formulation (actually, a double exponential) for the penetrative shortwave radiation.

2.7 Subgrid scale parameterizations

Here, we outline some features of the subgrid scale parameterizations available in MOM4p1.

- Horizontal friction: MOM4p1 has a suite of horizontal friction schemes, such as Smagorinsky laplacian and biharmonic schemes described in Griffies and Hallberg (2000) and the anisotropic laplacian scheme from Large et al. (2001) and Smith and McWilliams (2003). Code for these schemes is found in the modules

`mom4/ocean_param/mixing/ocean_lapgen_friction`
`mom4/ocean_param/mixing/ocean_bihgen_friction`.

- Convection: There are various convective methods available for producing a gravitationally stable column, with the code found in the module

  `mom4/ocean_param/mixing/ocean_convect`.

  The scheme used most frequently at GFDL is that due to Rahmstorf (1993).

- NEUTRAL PHYSICS AND BOUNDARY REGIONS: There are new options available for treating neutral physics within boundary regions, as motivated from ideas proposed by Ferrari et al. (2008). A discussion of these ideas is given in Chapter 16 of this document, and the code is available in the module

  `mom4/ocean_param/mixing/ocean_nphysicsB`,

  with the MOM4.0 methods remaining in

  `mom4/ocean_param/mixing/ocean_nphysicsA`.

  There are also some further methods implemented in

  `mom4/ocean_param/mixing/ocean_nphysicsC`

  based on the work of Ferrari et al. (2009). Note that the nphysicsC module remains experimental, and so should *not* be used for general applications.

- RESTRATIFICATION EFFECTS FROM SUBMESOSCALE EDDIES: There is an option available for parameterizing the restratification effects from submesoscale eddies, as proposed by Fox-Kemper et al. (2008b). The MOM4p1 formulation is given in Chapter 18, and the code is available in the module

  `mom4/ocean_param/mixing/ocean_submesoscale`.

- FORM DRAG: MOM4p1 has various options associated with the parameterization of form drag arising from unresolved mesoscale eddies, as proposed by Greatbatch and Lamb (1990), Aiki et al. (2004), and Ferreira and Marshall (2006). The code is available in the module

  `mom4/ocean_param/mixing/ocean_form_drag`,

  and documentation is given in Chapter 17. The form drag parameterization schemes are experimental and have not been thoroughly used at GFDL.

- TIDAL MIXING PARAMETERIZATION: The tidal mixing parameterization of Simmons et al. (2004) has been implemented as a means to parameterize the diapycnal mixing effects from breaking internal gravity waves, especially those waves influenced by rough bottom topography. Additionally, this scheme has been combined with that used by Lee et al. (2006), who discuss the importance of barotropic tidal energy on shelves for dissipating energy and producing tracer mixing. Chapter 14 presents the model formulation, and

  `mom4/ocean_param/mixing/ocean_vert_tidal`

  contains the code.

- Other vertical mixing schemes: MOM4p1 comes with an array of vertical mixing schemes, such as the following.

  - Constant background diffusivity proposed by Bryan and Lewis (1979)

    `mom4/ocean_param/mixing/ocean_vert_mix`

  - Richardson number dependent scheme from Pacanowski and Philander (1981)

    `mom4/ocean_param/mixing/ocean_vert_pp`

  - The KPP scheme from Large et al. (1994)

    `mom4/ocean_param/mixing/ocean_vert_kpp`
    `mom4/ocean_param/mixing/ocean_vert_kpp_mom4p0`

    The module `ocean_vert_kpp` maintains code provides some code updates relative to MOM4.0, such as to allow for the use of generalized vertical coordinates; features found useful in fresh inland seas; and modifications introduced by Danabasoglu et al. (2006). The module `ocean_vert_kpp_mom4p0` maintains code compatibility with the implementation of MOM4.0 necessary to allow for backwards compatiblity with the CM2.1 coupled model documented in Griffies et al. (2005).

  - GENERAL OCEAN TURBULENCE MODEL (GOTM): Coastal simulations require a suite of vertical mixing schemes beyond those available in most ocean climate models. GOTM (Umlauf et al., 2005) is a public domain Fortran90 free software used by a number of coastal ocean modellers

    `http : //www.gotm.net/`

    GOTM includes many sophisticated turbulence closure schemes, and is updated periodically. It thus provides users of MOM4p1 access to most updated methods for computing vertical diffusivities and vertical viscosities. GOTM has been coupled to MOM4p1 by scientists at CSIRO in Australia in collaboration with German and GFDL scientists.
    The MOM4p1 wrapper for GOTM is

    `mom4/ocean_param/mixing/ocean_vert_gotm`

    with the GOTM source code in the directory

    `mom4/ocean_param/gotm`.

- UPDATE OF OVERFLOW SCHEMES: MOM4p1 comes with various methods of use for parameterizing, or at least facilitating the representation of, dense water moving into the abyss. These schemes are documented in Chapter 19, with the following modules implementing these methods

  mom4/ocean_param/mixing/ocean_sigma_transport
  mom4/ocean_param/mixing/ocean_mixdownslope
  mom4/ocean_param/sources/ocean_overflow
  mom4/ocean_param/sources/ocean_overexchange.

2.8 Miscellaneous features

Here, we outline some miscellaneous features of MOM4p1.

- REFINED OPEN BOUNDARY CONDITIONS MODULE: Much of the appeal of MOM4p1 is related to its enhanced facilities for regional ocean modeling, with Herzfeld et al. (2010) documenting certain of these features. Central to this utility is the enhanced open boundary condition module

  mom4/ocean_core/ocean_obc

  which is documented in Chapter 12 as well as Herzfeld et al. (2010).

- UPDATED SPURIOUS MIXING DIAGNOSTIC: Griffies et al. (2000b) describe an empirical diagnostic method to diagnose the levels of mixing occurring in a model. This diagnostic required some upgrades to allow for the use of thickness weighting for time stepping the prognostic fields (see Chapter 23, especially Section 23.3). This code is available in the module

  mom4/ocean_diag/ocean_tracer_diag.

  Also, the method of Burchard and Rennau (2008) is available in MOM4p1 to diagnose the dissipation associated with numerical advection. Details of the MOM4p1 implementation of this diagnostic are provided in Chapter 24.

- STERIC SEA LEVEL DIAGNOSTIC: We compute the steric sea level diagnostically for the case when running a Boussinesq model. The formulation is given in Chapter 26.

- REVISED TEST CASES: All of the test cases have been revised as well as the addition of some new tests. As in MOM4.0, the tests are **not sanctioned for their physical realism.** Instead, they are provided for computations and numerical evaluation, and as starting points for those wishing to design and implement their own research models.

- UPDATED FMS INFRASTRUCTURE AND PREPROCESSING TOOLS: As with all releases of MOM4, it comes with updated infrastructure, preprocessing code, coupling code, etc. supported by an array of scientists and engineers at GFDL.

2.9 Short bibliography of MOM4 documents

The following is an incomplete list of documents that may prove useful for those wishing to learn more about the MOM4 code, and some of its uses at GFDL.

- The MOM3 Manual of Pacanowski and Griffies (1999) continues to contain useful discussions about issues that remain relevant for MOM4.
- The MOM4 Technical Guide of Griffies et al. (2004) aims to document the MOM4.0 code and its main features.
- The present document, Griffies (2009), presents the fundamental formulation and model algorithms of use for the generalized vertical coordinate code MOM4p1.
- The monograph by Griffies (2004) presents a pedagogical treatment of many areas relevant for ocean climate modellers.
- The paper by Griffies et al. (2005) provides a formulation of the ocean climate model used in the GFDL CM2 climate model for the study of global climate variability and change. The ocean code is based on MOM4.0.
- The paper by Gnanadesikan et al. (2006a) describes the ocean simulation characteristics from the coupled climate model CM2.
- The paper by Delworth et al. (2006) describes the coupled climate model CM2.
- The paper by Wittenberg et al. (2006) focuses on the tropical simulations in the CM2 coupled climate model.
- The paper by Stouffer et al. (2006) presents some idealized climate change simulations with the coupled climate model CM2.
- The paper by Herzfeld et al. (2010) documents the use of MOM4p1 for regional modeling.

2.10 The future of MOM

MOM has had a relatively long and successful history. The release of MOM4p1 represents a major step at GFDL to move into the world of generalized level coordinate models, as well as regional modeling. It is anticipated that MOM4p1 will be used at GFDL and abroad for many process, coastal, regional, and global studies. It is, quite simply, the most versatile of the MOM codes produced to date.

Nonetheless, there are many compelling reasons to move even further along the generalization path, in particular to include isopycnal layered models in the same code base as the level vertical coordinates enabled in MOM4p1. As discussed in Griffies et al. (2000a), there remain many systematic problems with each vertical coordinate class, and such warrants the development of a single code base that can examine these issues in a controlled setting.

GFDL employs the developers of three of the world's most successful ocean model codes: (1) Alistair Adcroft, who developed the MITgcm, which has non-hydrostatic and hydrostatic options;

(2) Bob Hallberg, who developed the Hallberg Isopycnal Model, which has been used for process studies and global coupled modelling, and (3) Stephen Griffies, who has been working on MOM development. A significant step forward in ocean model code will be found by merging various features of the MITgcm, HIM, and MOM. Therefore, Adcroft, Griffies, and Hallberg have each agreed to evolve their efforts towards the goal of producing a GFDL Unified Ocean Model. Public release of this code will occur at an uncertain date, likely after 2012.