# Ocean Modeling at GFDL
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**Abstract**

GFDL develops and uses two ocean models for various applications, mostly centered on climate science questions. The Modular Ocean Model (MOM4p1) is the latest in a long line of MOM codes at GFDL, with MOM4p1 based on a finite volume implementation of generalized level coordinates. The Generalized Ocean Layer Dynamics (GOLD) is an layered isopycnal model that originates from the earlier Hallberg Isopycnal Model (HIM). The purpose of this report is to summarize certain of the research and development efforts ongoing at GFDL where the ocean codes MOM and GOLD are key. Where suitable, we distinguish between the distinct, but tightly coupled, roles of model configuration development from code development.

## Contents

## 1 Two comments about GFDL ocean codes

We present here two general comments regarding the development of algorithms with ocean models at GFDL.

### 1.1 Conservation of mass and tracers

A fundamental constraint on an ocean model code for use in climate science studies is that the ocean model must conserve mass (or volume for a Boussinesq model) and tracer, ideally to within computational roundoff. That is, the numerical algorithms ideally should be exactly conservative of all scalar fields. Absent this constraint, models generally exhibit spurious features that corrupt their use for long term (order century to millenia) climate and earth system simulations. In particular, without conservation of heat, it is unclear whether an earth system model using this ocean component will reach an equilibrium state when integrated for the millenial time scales required for earth system studies with prognostic biogeochemistry.

The conservation of scalars is not satisfied by the most popular community layered model HYCOM. In particular, as noted by Megann et al. (2011), HYCOM exhibits roughly 0.5 W m$^{-2}$ non-conservation of heat when globally averaged, with this non-conservation arising from algorithm limitations. This level of heat non-conservation is unacceptable for climate applications, where the signal from climate change is on the order of 1 W m$^{-2}$.

Given that MOM and GOLD were developed for use as components to a coupled climate model, amongst other applications, the requirements of scalar conservation were at the forefront of algorithm developments with these codes. MOM and GOLD both conserve scalars to within computational roundoff. That is, their numerical algorithms exactly conserve seawater mass and tracer mass.

## 1.2 Virtual tracer fluxes versus real water fluxes

True water fluxes have been standard in HIM, MOM3, GOLD, and MOM4 for more than a decade. For MOM, this work was initiated by the implementation of an explicit free surface algorithm by Griffies et al. (2001). The split-explicit free surface method is now standard for ocean climate modeling, with both MOM and GOLD (see Hallberg and Adcroft, 2009, for the method used in GOLD). Although not representing a new development at GFDL, we believe it useful to here emphasize why it is very useful to climate studies to employ ocean models admitting the transport of water across its surface boundary.

As discussed in Huang (1993), Griffies et al. (2005), and Yin et al. (2010), the real water boundary condition provides for the following improvements in model formulation and behavior.

- Salt within the ocean is constant, except for the small amounts exchanged with the sea ice model (which uses a constant salinity of 5ppt). The use of a real water flux allows for one to track the budget of salt and fresh water in a physically relevant manner.
- There are more realistic feedbacks associated with rivers, precipitation, and evaporation.
- The Goldsbrough-Stommel circulation is admitted, as it is driven by hydrological forcing.
- The formulation of surface boundary conditions for ocean biogeochemical models is far more natural when using real water fluxes.
- There are barotropic signals and mass redistributions associated with the exchange of water with other climate components. As highlighted by Kopp et al. (2010), the ability to exchange mass with other climate components facilitates studies of how mass redistributions in the climate system impact the earth's gravity field and rotation, both of which are critical for understanding and quantifying sea level change.

MOM4p1 retains the option of using virtual salt fluxes. However, this option is steadily becoming obsolete, as all climate model configurations used at GFDL employ real water fluxes.

# 2 Code development with GOLD

The Generalized Ocean Layer Dynamics (GOLD) is an isopycnal code having evolved from the earlier Hallberg Isopycnal Model (HIM). During recent years, GOLD has undergone a significant improvement in algorithms and expansion of its applications towards global climate. The following represents a summary of the code developments and applications that are not covered in subsequent sections of this report.

## 2.1 Algorithm developments

The following summarizes major algorithm developments with GOLD made during recent years.

### 2.1.1 Reconciling estimates for the surface height in layered models

Non-conservation of mass and tracer in layered models remains a troubling feature of these models for use in climate applications. One reason for the non-conservation relates to differences in estimates of the surface height within two different portions of the model algorithm. Hallberg and Adcroft (2009) present a method that removes the ambiguity, which in turn removes the associated problems with nonconservation. Other problems related to numerical instabilities and unphysically large amplitude barotropic waves are resolved as well.

More precisely, the following is a slightly edited abstract from the Hallberg and Adcroft (2009) paper.

> In ocean models that use a mode splitting algorithm for time-stepping internal and external gravity modes, the external and internal solutions each can be used to provide an estimate of the free surface height evolution. In level coordinate models, it is standard to force the internal solutions for the free surface height to agree with the external solution by specifying

> the appropriate vertically averaged velocities. Because this is a linear problem in level models, it is relatively straightforward. However, in Lagrangian vertical coordinate ocean models with potentially vanishing layers, nonlinear discretizations of the continuity equations must be used for each interior layer in order to ensure positive definite layer thickness. Hallberg and Adcroft (2009) discuss options for enforcing agreement between the internal and external estimates of the free surface height, along with the consequences of each choice, and suggests an optimal, essentially exact, approach.

### 2.1.2 A finite volume method to compute the pressure gradient in layered models

Layered ocean models can exhibit spurious thermobaric instability if the compressibility of sea water is not treated accurately enough. We have found that previous solutions to this problem are inadequate for simulations of a changing climate. Adcroft et al. (2008) propose a new discretization of the pressure gradient acceleration using the finite volume method. In this method, the pressure gradient acceleration is exhibited as the difference of the integral "contact" pressure acting on the edges of a finite volume. This integral "contact" pressure can be calculated analytically by choosing a tractable equation of state. The result is a discretization that has zero truncation error for an isothermal and isohaline layer and does not exhibit the spurious thermobaric instability.

### 2.1.3 Accurate remapping for generalized vertical coordinate models

In order to provide an accurate generalized vertical coordinate model, one must employ a very accurate remapping scheme, which is analogous to an accurate vertical advection scheme. White and Adcroft (2008) and White et al. (2009) present a hierarchy of one-dimensional high-order remapping schemes, as well as their performance with respect to accuracy and convergence rate. Here are the abstracts for these two papers.

> (White and Adcroft, 2008): A hierarchy of one-dimensional high-order remapping schemes is presented and their performance with respect to accuracy and convergence rate investigated. The schemes are also compared based on remapping experiments in closed domains. The piecewise quartic method (PQM) is presented, based on fifth-order accurate piecewise polynomials, and is motivated by the need to significantly improve hybrid coordinate systems of ocean climate models, which require the remapping to be conservative, monotonic and highly accurate. A limiter for this scheme is fully described that never decreases the polynomial degree, except at the location of extrema. We assess the use of high-order explicit and implicit (i.e., compact) estimates for the edge values and slopes needed to build the piecewise polynomials in both piecewise parabolic method (PPM) and PQM. It is shown that all limited PQM schemes perform significantly better than limited PPM schemes and that PQM schemes are much more cost-effective.
>
> (White et al., 2009): A hierarchy of high-order regriddingremapping schemes for use in generalized vertical coordinate ocean models is presented. The proposed regriddingremapping framework is successfully used in a series of idealized one-dimensional numerical experiments as well as two-dimensional internal wave and overflow test cases. The model is capable of replicating z-, sigma- and isopycnal-coordinate results, among others. Particular emphasis is placed on the design of a continuous isopycnal framework, which is a more general alternative to the layered isopycnal paradigm. Continuous isopycnal coordinates use target interface densities to define layers. In contrast to traditional layered isopycnal models, in which along-layer density gradients vanish, general coordinate approaches must deal with extra terms. For example, the calculation of pressure gradient force is more complicated and must be evaluated carefully. High-order reconstructions within boundary cells are crucial for obtaining sensible results and for reducing spurious diffusion near boundaries. Vertical advection is implicitly embedded in the remapping step and directly benefits from high-order schemes. Volume and all tracers are conserved to machine precision, which is a necessary ingredient for long-term ocean climate

modeling. This hybrid vertical coordinate model provides the framework to easily capture the impact of different coordinate systems on dynamics.

### 2.2 Application to Gulf of Mexico oil spill

Adcroft et al. (2010) present results from a simple model of the temperature-dependent biological decay of dissolved oil in a 1/8° global simulation with GOLD. This model is used to simulate underwater plumes of dissolved and suspended oil originating from a point source in the northern Gulf of Mexico. Plumes at different source depths are considered and the behavior at each depth is found to be determined by the combination of sheared current strength and vertical profile of decay rate. An upper bound on the supply rate of dissolved and suspended oil is estimated for the interior water column from contemporary analysis of the Deepwater Horizon blowout. For all plume scenarios, toxic levels of dissolved oil are found to remain confined to the northern Gulf of Mexico, and abate within a few weeks after the spill stops. An estimate of oxygen consumption due to microbial oxidation of oil suggests that the presence of oil alone will not lead to hypoxia, but a deep plume of oil and methane (which dissolves readily in water) does lead to localized regions of persistent hypoxia and anoxia in the vicinity of the source.

### 2.3 Plans for GOLD code development

GOLD remains a layered isopycnal model. However, the remapping work from White and Adcroft (2008) and White et al. (2009) provides the framework to make it a fully generalized Lagrangian vertical coordinate model, with specific vertical coordinate choices being geopotential, pressure, terrain following, layered isopycnal, continuous isopycnal, and hybrids of these coordinates or others. This generalization requires enhancements to the dynamical core of GOLD, as well as the implementation of key physical parameterizations (e.g., neutral physics and KPP vertical mixing) and analysis methods now available in MOM. Each stage of this work is nontrivial, with the full work requiring some years before reaching a mature state.

Until such time as GOLD is fully generalized, it will continue to be used as a layered isopycnal model for use in studying climate relevant phenomena. One area of intense research and development concerns the study of ocean and ice-shelf interactions. Because GOLD allows for vanishing layers, it can be readily applied in a dynamic geometry, such as occurs when land ice shelves retreat upon melting. This work is targeted both at understanding the processes active at the ocean and ice shelf boundary, as well as to enhance the skill and utility of modeling tools used to study sea level rise.

In addition to studies of ice shelves, there are plans to develop a resolution hierarchy of simulations with GOLD using the interannually varying CORE forcing of Large and Yeager (2009). The 1/8° model used to study the Gulf of Mexico oil spill (Section 2.2) forms one element in this hierarchy.

Finally, development of a conservative two-way nesting algorithm is a longstanding goal for both MOM and GOLD, with coastal applications the main driver of this development. Work remains ongoing, in collaboration with similar efforts at GFDL to generalize the two-way moving mesh model used for hurricane forcasting.

## 3 Code development with MOM4p1

Since the release of MOM4.0 in 2004, there have been developments leading to various releases of MOM4p1, with 18Dec2009 being the most recent public release. These developments center on the following key features.

- Generalized level coordinates (Section 3.1)
- Physical parameterizations (Section 4.4)
- Tracer advection (Section 4.4)
- Dynamically interacting Lagrangian parcels (Section 3.2.1)
- Regional modeling (Section 5)

The remainder of this section summarizes developments with generalized level coordinates, embedded Lagrangian modeling, and online diagnostics. We also provide some comment in Section 1.2 concerning the problems for climate modeling associated with virtual tracer fluxes.

## 3.1 Generalized level coordinates

Adcroft and Hallberg (2006) distinguish Eulerian from Lagrangian vertical coordinate algorithms through their methods used to compute the cross coordinate advective velocity component. Eulerian algorithms diagnose their vertical velocity via the continuity equation, whereas Lagrangian algorithms specify it according to physical closure. The generalized level coordinate version of MOM4p1 follows the Eulerian method, whereas the layered models GOLD and HYCOM follow the Lagrangian method.

The discrete equations of MOM4p1 are formulated from a finite volume implementation of generalized level coordinates. Generalized levels provide a framework to implement many vertical coordinate options, such as geopotential, pressure, and terrain following. Although generalized, the equations within MOM4p1 are very similar to the earlier geopotential coordinate model MOM4.0. In particular, nearly all of the physical parameterizations retain the same basic code elements, thus facilitating the transition from geopotential to generalized level.

Of fundamental importance to the algorithms in MOM4p1 is the mass per unit area of a grid cell, $\rho\,\mathrm{d}z$. For the Boussinesq version of MOM4p1, $\rho\,\mathrm{d}z = \rho_0\,\mathrm{d}z$, with $\rho_0$ a constant reference density and $\mathrm{d}z$ is the time dependent grid cell thickness. For the non-Boussinesq version of MOM4p1, $\rho\,\mathrm{d}z$ is the instantaneous mass per area of the cell. Time stepping of the mass per area of a grid cell is based on solving the mass continuity equation for each cell. In MOM4.0, it was only the surface grid cell that allowed for the thickness to fluctuate. In MOM4p1, all grid cells generally have time dependent thickness and mass.

In the process of generalizing the continuity equation, we introduced to MOM4p1 the ability to specify an arbitrary mass source/sink for each grid cell. Namely, one may consider a "parameterization" whereby mass is moved non-locally from one cell to another, such as via the overflow scheme of Danabasoglu et al. (2011). By including mass sources in the continuity equation, MOM4p1 allows the dynamics to directly adjust to the movement of mass, rather than by specifying a recirculation of mass as required in the absence of mass sources. Such recirculation schemes are, for example, central to the original implementation of the sigma advection scheme of Beckmann and Döscher (1997) and the overflow scheme of Campin and Goosse (1999). This added feature of the mass continuity equation is quite trivial to include in an explicit free surface model. It constitutes an essential element in the development of an interactive Lagrangian model embedded within MOM (Section 3.2.1).

MOM4p1 retains the constraint that no vertical level can disappear within a simulation, with this constraint central to all existing level coordinate models. This constraint greatly simplifies the algorithms. However, it limits applications to cases where land-sea boundaries are fixed. Such applications are pertinent for coupling ocean and ice shelf models, with such coupling of interest for studying questions of sea level rise. Wetting and drying algorithms exist within Eulerian model frameworks (Oey, 2005), though we know of no application with MOM4 using such algorithms. Wetting and drying algorithms are naturally coded in layered models, such as GOLD, that allow for vanishing isopycnal layers (see Section 2.3).

### 3.1.1 Six vertical coordinates implemented in MOM4p1

MOM4p1 has the following six vertical coordinates implemented within its generalized layer framework.

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

$$s = z. \tag{1}$$

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

$$\begin{aligned} s &= z^* \\ &= H\left(\frac{z-\eta}{H+\eta}\right). \end{aligned} \tag{2}$$

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

$$
\begin{aligned}
s &= \sigma^{(z)} \\
&= \frac{z-\eta}{H+\eta}.
\end{aligned} \tag{3}
$$

- Pressure coordinate

$$
s = p. \tag{4}
$$

- Quasi-horizontal rescaled pressure coordinate

$$
\begin{aligned}
s &= p^{*} \\
&= p_{\mathrm{b}}^{o}\left(\frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}\right),
\end{aligned} \tag{5}
$$

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

- Pressure based terrain following coordinate

$$
\begin{aligned}
s &= \sigma^{(p)} \\
&= \left(\frac{p-p_{\mathrm{a}}}{p_{\mathrm{b}}-p_{\mathrm{a}}}\right).
\end{aligned} \tag{6}
$$

Note the following points in regards to the implementation of these vertical coordinates.

- All depth based vertical coordinates implement the volume conserving, Boussinesq, ocean primitive equations.
- All pressure based vertical coordinates implement the mass conserving, non-Boussinesq, ocean primitive equations.
- There has been little effort focused on reducing pressure gradient errors in the terrain following coordinates implemented in MOM4p1. 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 with terrain following coordinates is not recommended with the present implementation in MOM4p1. There are formulation issues that have not been addressed in the literature. The main focus of neutral physics applications at GFDL centres on vertical coordinates that are quasi-horizontal, including $z, p, z^{*}$ and $p^{*}$.

### 3.1.2 Advantages of $z^{*}$ for climate modeling

We comment now on certain advantages of the stretched vertical coordinates $z^{*}$ and $p^{*}$ over their unstretched cousins $z$ and $p$. The following discusses the $z^{*}$ coordinate in particular. But $p^{*}$ shares similar advantages via the isomorphism detailed by Marshall et al. (2004).

Whereas a geopotential ocean model places all free surface undulations into the top model grid cell, a $z^{*}$ model distributes the undulations throughout the ocean column. All grid cells thus have a time dependent thickness with $z^{*}$. Surfaces of constant $z^{*}$ differ from geopotential surfaces according to the ratio $\eta/H$, which is generally quite small, where $\eta$ is the free surface undulation relative to $z = 0$, and $z = -H(x, y)$ is the ocean bottom. Hence, surfaces of constant $z^{*}$ are quasi-horizontal, thus reducing difficulties of accurately computing the horizontal pressure gradient relative to the case of terrain following sigma coordinates (see Griffies et al., 2000, for a review). The $z^{*}$ vertical coordinate is analogous to the "eta" coordinate sometimes used for atmospheric models (Black, 1994).

Climate modelers may wish to choose $z^*$ over $z$ for its enhanced flexibility when considering two key applications of climate models. The first application concerns large surface height deviations associated with tides and/or increased loading from sea ice (e.g., a global cooling simulation). The $z^*$ model allows for the free surface to fluctuate to values as large as the local ocean depth, $|\eta| < H$, whereas the geopotential model is subject to the more stringent constraint $|\eta| < \Delta z_1$, with $\Delta z_1$ the thickness of the top grid cell with a resting ocean. This flexibility with $z^*$ is further exploited if considering even finer vertical grid resolution. The second application where $z^*$ is useful concerns increased land ice melt that adds substantially to the sea level, as in the idealized studies of Stouffer et al. (2006b), Kopp et al. (2010), and Yin et al. (2010). Placing all of the surface expansion into the top model grid cell, as with the free surface geopotential model, greatly coarsens the vertical grid resolution in this important portion of the ocean, whereas the $z^*$ model does not suffer from this problem since the expansion is distributed throughout the column.

#### 3.1.3 Advantages of $p^*$ for climate modeling

The stretched pressure coordinate $p^*$ supports the advantages of $z^*$ listed above, with the added element of directly representing the steric component of sea level since the model integrates the non-Boussinesq mass conserving primitive equations. Although early studies comparing Boussinesq and non-Boussinesq simulations indicate there should be no surprises (Greatbatch, 1994; Mellor and Ezer, 1995; Losch et al., 2004), none of these studies considered realistic coupled climate simulations. Direct comparisons of Boussinesq and non-Boussinesq versions of CM2.1 are ongoing.

### 3.2 Plans for MOM4p1 code development

MOM4p1 remains a central component of many science applications at GFDL and elsewhere. Plans are to continue developing it, with emphasis on enhancing parameterizations, numerical methods, and analysis techniques. The following is a sampling of the main developments planned for the near future.

#### 3.2.1 Embedded dynamically interacting Lagrangian parcels

A Lagrangian framework for representing open ocean convection and near boundary convection has been developed within MOM4p1 by Michael Bates, a graduate student in Sydney, Australia. The Lagrangian framework arbitrarily re-labels parcels of fluid in a grid cell that can then be treated pseudo-independently from the gridded model. The parcels, or blobs, can then be moved around in three dimensions and interact with the Eulerian model in an arbitrary manner. In doing so, blobs can effect transport of properties vertically through the water column and laterally. The technique is not a parameterisation, but rather a framework in which a multitude of parameterisations may be implemented. As such, it is possible to recover parameterisations which are analogous to many existing and commonly used parameterisations, for both upright convection and downslope flows.

One of the most promising aspects of this approach is that it permits dynamics, allowing the blobs to move and respond to the bulk ocean properties and physics in a realistic way. Furthermore, the framework permits pseudo non-hydrostatic dynamics, which essentially allows the blob to sink (either in the open ocean, or along topography) if it is surrounded by water that is less dense. Another promising aspect of the framework is that it permits explicit entrainment and detrainment by the transfer of properties from an Eulerian grid box to a Lagrangian blob and vice versa. This framework potentially allows for a more complete and physically based representation of open ocean convection and downslope flows.

Plans are to fully develop the algorithm within the remainder of 2010, and to test it within idealized and realistic ocean model configurations. There are hopes that this approach may provide modelers with a more fundamental approach to representing convection and downslope flows in climate model applications.

#### 3.2.2 Online water mass transformation analysis tools

The water mass transformation method has been developed in the years since the pioneering work of Walin (1982), and further explored and generalized by Tziperman (1986), Speer and Tziperman (1992), Marshall et al. (1999), Viúdez (2000), Large and Nurser (2001), and Iudicone et al. (2008). Ongoing work at GFDL and Princeton University aims to bring the elements of these analysis methods into MOM4p1 for online diagnostic computations. Providing these tools online will facilitate a far more detailed deductive diagnosis of the causes of dianeutral transport within the ocean interior.

### 3.2.3 Two way nesting

Development of a conservative two-way nesting algorithm is a longstanding goal for both MOM and GOLD, with coastal applications the main driver of this development. Work remains ongoing, in collaboration with similar efforts at GFDL to generalize the two-way moving mesh model used for hurricane forcasting.

# 4 Climate and earth system modeling

The main focus of numerical ocean modeling research and development at GFDL concerns questions of climate science. During recent years, there has been the development of a suite of climate and earth system models, from intermediate complexity to fully realistic. Some of these efforts involved a large group of scientists, whereas others represent the efforts of only a few individuals, including post-doctoral scientists. The purpose of this section is to briefly summarize these models, with focus given to the ocean components.

## 4.1 CM2.1

The CM2.1 coupled climate model (Delworth et al., 2006; Griffies et al., 2005; Gnanadesikan et al., 2006; Wittenberg et al., 2006; Stouffer et al., 2006a; Russell et al., 2006) was completed in 2004 for IPCC AR4 science and projections. Although now outdated in some process physics and numerical algorithm aspects, a significant number of studies indicate that CM2.1 is the benchmark for future development of models at GFDL and elsewhere. The CM2.1 configuration was released through the 18Dec2009 public release of MOM4p1. This release of CM2.1 is the first general release of a GFDL coupled climate model configuration.

CM2.1 remains in use at GFDL for IPCC AR5 applications aimed at the decadal prediction component of CMIP5. An assimilation system has been constructed based on CM2.1 (ref Zhang et al paper), with an upgraded ocean model component using the MOM4p1 code of Griffies (2009). The assimilation system is used for ocean reanalysis and initialization of climate prediction simulations. Plans are to conduct prediction experiments with this model based on 40 initial conditions (1970-2010), each run for 10 years using 10 ensemble members each (4000 years of simulation). Ensemble members use the same ocean initial conditions, with atmosphere initial conditions shifted by a few days. This approach helps to establish an upper limit on predictability of the variability simulated by this model.

## 4.2 ESM2.1

CM2.1 forms the physical basis for one of GFDL's first earth system modeling efforts, ESM2.1. This model was constructed with early versions of the GFDL land and vegetation models, and was an important proto-type for the ESM2M and ESM2G models discussed later. In particular, ESM2.1 uses only potential vegetation, so has no land use included. It uses the GFDL-developed ocean biogeochemistry model TOPAZ.

ESM2.1 has been successfully run to millenial scale equilibrium using 1860 radiative forcing, and has been used for historical (1860-2000) and AR4 21st century warming scenarios. ESM2.1 produces a climate similar to CM2.1, but with some differences attributable to the interactive biogeochemistry in the ocean as represented by TOPAZ. Plans are underway to document these simulations. Additionally, there are plans to use ESM2.1 for millenial scale paleoclimate simulations focusing on the last glacial maximum.

## 4.3 CM3

Subsequent to the develoment of CM2.1, GFDL focused on two main development paths toward high-end models of use for AR5 and beyond. One avenue focused on atmospheric component priorities, including aerosol-cloud interactions, chemistry-climate interactions, and links between the troposphere and stratosphere. Updates to the land model used for ESM2M/G were also incorporated. To help achieve a state-of-the-science climate model tool using the new atmospheric model, in time for the AR5, we chose to keep the ocean and sea ice components of CM3 effectively the same as in CM2.1. Hence, CM3 uses the MOM4p1 code configured nearly as in CM2.1, with the single exception that the vertical grid uses the stretched geopotential coordinate $z^*$ proposed by Stacey et al. (1995) and Adcroft and Campin (2004). Documentation of CM3 is given by Donner et al. (2010) (atmospheric component) and Griffies et al. (2010) (ocean and sea ice components).

## 4.4 CM2M

The second path toward AR5 models emphasized the needs of earth system modeling, in which interactive ocean biogeochemistry, land vegetation, and interactive carbon cycling are critical. This path used nearly the same atmospheric model as in CM2.1, and it led to two new earth system models, known as ESM2M and ESM2G, that differ only by their ocean components. The physical component of ESM2M consists of CM2M, which uses MOM4p1 as the ocean component.

For CM2M, MOM4p1 is configured with the same horizontal and vertical grid dimensions as CM2.1, but with the stretched geopotential coordinate $z^*$ vertical coordinate, as in CM3. Additional updates to the physical parameterization and numerical methods are included in CM2M, with the following a summary of these updates.

- Tracer advection: The tracer advection scheme in CM2.1 was based on a third order upwind biased approach of Hundsdorfer and Trompert (1994) who employ the flux limiters of Sweby (1984). This implementation of numerical advection is non-dispersive, preserves shapes in three dimensions, and precludes tracer concentrations from moving outside of their natural ranges. For CM2M, we chose the multi-dimensional piecewise parabolic method (MDPPM) ported from the MITgcm by Alistair Adcroft. In idealized simulations, the MDPPM method was found to be more accurate (less diffusive) than the CM2.1 advection scheme, while still preserving monotonicity. The computational cost of MDPPM is comparable to the CM2. scheme.

  On the way to choosing MDPPM for CM2M, we tested the second moment scheme from Prather (1986), and further developed for sea ice modeling by Merryfield and Holloway (2003) and Maqueda and Holloway (2006). Our experience with the Prather scheme was mixed. Namely, in idealized studies, it performed wonderfully. However, in realistic applications, it required the introduction of flux limiters to retain tracers within physically relevant bounds. Use of these flux limiters in idealized tests brought the results down to the level of the MDPPM scheme. Given the extreme computational and memory cost of the Prather scheme, we chose to use the MDPPM scheme instead.

- Neutral diffusion: The neutral diffusion scheme for both CM2.1 and CM2M is based on the methods of Griffies et al. (1998); both use a constant diffusivity of $600\text{m}^2\ \text{s}^{-1}$; and both use the slope tapering scheme of Danabasoglu and McWilliams (1995). However, CM2.1 uses the rather small value of 1/500 for the maximum slope parameter, whereas CM2M uses the larger value of 1/50.

- Parameterized mesoscale eddy induced stirring: Both CM2.1 and CM2M employ a parameterization of mesoscale eddy-induced advection. CM2.1 follows the approach of Gent and McWilliams (1990) and Gent et al. (1995), as implemented by a skew diffusion operator detailed by Griffies (1998). The transition to an upper ocean boundary layer follows the methods of Treguier et al. (1997) and Large et al. (1997) (see also chapter 15 of Griffies (2004)). Again, the maximum slope of 1/500 was chosen, at which point the GM-streamfunction saturates to its maximum value. Finally, the horizontal variation of the eddy diffusivity was determined according to the local flow properties, as detailed in Griffies et al. (2005). The eddy diffusivity is bounded between the values of $100\text{m}^2\ \text{s}^{-1}$ and $600\text{m}^2\ \text{s}^{-1}$.

  CM2M shares only one element with CM2.1 in its parameterization of mesoscale eddy induced stirring. Namely, calculation of the eddy diffusivity is the same, yet the range is allowed to extend between $100\text{m}^2\ \text{s}^{-1}$ and $800\text{m}^2\ \text{s}^{-1}$. The main difference with CM2.1 concerns the use of the new formulation from Ferrari et al. (2010), in which the eddy-induced quasi-Stokes streamfunction is computed via a boundary value problem extending from the ocean floor to surface. That is, the streamfunction is a function of the full column stratification, rather than the local approach proposed by Gent and McWilliams (1990) and Gent et al. (1995). The Ferrari et al. (2010) approach has no maximum slope paramter, yet there are other parameters that can act in a similar manner. Testing of this scheme remains ongoing, especially with a focus on sensitivity to changes in wind stress in the Southern Ocean (Farneti et al., 2010).

- PARAMETERIZED MIXING FROM TIDES: Both CM2.1 and CM2M use the barotropic tide mixing scheme from Lee et al. (2006). However, CM2.1 uses a prescribed background diffusivity motivated by Bryan and Lewis (1979). In contrast, CM2M replaces the Bryan and Lewis (1979) background with a baroclinic tide mixing scheme developed by Simmons et al. (2004).
- LATERAL FRICTION: CM2.1 used the horizontal anisotropic friction scheme from Large et al. (2001). CM2M chose to use an isotropic Laplacian friction and a western boundary enhanced biharmonic friction. The net effect is that CM2M has less frictional dissipation, allowing, in particular, the representation of a vigorous tropical instability wave activity. The cost of reducing the viscosity is the presence of some enhanced grid noise, especially in the tropics.
- UPPER OCEAN BOUNDARY LAYER: The KPP mixing scheme of Large et al. (1994) is used by both CM2.1 and CM2M to parameterize mixing in the upper ocean. This scheme includes a parameterization of double diffusion, penetrative convection, shear induced mixing, and a bulk profile allowing for a sensible parameterization with coarse vertical resolution. The CM2M implementation includes a few updates based on input from NCAR.

## 4.5 ESM2M

ESM2M uses the physical model CM2M at its core, with prognostic ocean biogeochemistry and fully interactive carbon cycle through the ocean, land, and atmosphere. ESM2M has been recently spun-up for ~2000y using pre-industrial radiative forcing. After about 2000 years, it reached a stable climate equilibrium with a global mean ocean heat flux of less than 0.01 W $m^{-2}$, and a corresponding stable carbon cycle. Consistent with the millenial scale CM2.1 and ESM2.1 simulations, ESM2M equilibrates to an ocean state somewhat warmer than present day observations. This model is presently being integrated through the various CMIP5 scenarios.

## 4.6 CM2G

CM2G is the GOLD analog to CM2M. All components of CM2G are identical to CM2M, except that the ocean component is the layered isopycnal model GOLD. The physical parameterizations in CM2G parallel those in CM2M, with the following detailing the main features.

- UPPER OCEAN BOUNDARY LAYER: The upper ocean boundary layer is represented by a bulk mixed layer that allows for a parameterization of vertical shearing effects and a buffer layer for entrainment/detrainment effects (Hallberg, 2003). This mixed layer compares well, in one-dimensional column tests, to the KPP scheme used in CM2M.
- TIDE MIXING PARAMETERIZATIONS: CM2G has implemented the tide mixing parameterization of Simmons et al. (2004), with similar tuning of the energy influx performed as in CM2M. However, careful comparison of the mixing induced by this scheme in CM2M and CM2G remains an ongoing task.
- NEUTRAL PHYSICS: The neutral diffusion and eddy-induced advection each use the same diffusivity, with this diffusivity no larger than 300$m^2$ $s^{-1}$. The use of more realistically larger values resulted in an in increase in poleward heat transport in the Southern Ocean. Due to known limitations of the atmospheric component of CM2M and CM2G, the enhanced poleward heat transport resulted in large warm SST biases in the Southern Ocean.

CM2G has been integrated for several hundred years, with a stable climate state reached, including a steady Atlantic overturning circulation.

### 4.7 ESM2G

ESM2G uses the physical model CM2G at its core. That is, ESM2G is the GOLD analog to ESM2M. ESM2G has been recently spun-up for ~2000y. However, it has yet to reach a stable climate equilibrium state, with roughly $-0.2$ W m$^{-2}$ of heat leaving the ocean even after 2000y. The model is thus continuing to cool, which contrasts with the warm equilibrated state in ESM2M. This model is presently being integrated through the various CMIP5 scenarios.

### 4.8 CM2.5

CM2.5 uses a 1/4° configuration of MOM4p1 with the $z^*$ vertical coordinate. It is coupled to a 1/2° atmosphere model. The ocean component of CM2.5 is similar to that used for the CM2.4 model of Farneti et al. (2010). CM2.5 has been run for 200 years with 1990 radiative forcing, and is presently being run in an idealized $CO_2$ doubling experiment. Ongoing development of CM2.5 is focused on addressing biases in the North Atlantic subpolar gyre.

### 4.9 CM2Mc

As a post-doc with Jorge Sarmiento's group, Eric Galbraith developed CM2Mc, which is a coarsened version of CM2M with applications focused on millenial scale earth system modeling and paleoclimate. This model is documented by Galbraith et al. (2011), and it is available via the 18Dec2009 public release of MOM4p1.

### 4.10 ICCM

As a post-doc with Geoff Vallis, Riccardo Farneti developled a coupled model of intermediate complexity known as ICCM. This model is documented in Farneti and Vallis (2009a) and is available via the 18Dec2009 public release of MOM4p1. Atlantic variability exhibited by this model is described by Farneti and Vallis (2009b).

### 4.11 Hurricane research

GFDL scientists have pioneered the coupling of hurricane models to ocean models, illustrating the importance of the negative feedback from cold waters upwelling under slow moving hurricanes (Bender et al., 2000). These early efforts used the Princeton Ocean Model. Recently, however, the hurricane research has incorporated MOM4p1 as its ocean component, with plans to couple a fine resolution MOM configuration (either 1/4° or 1/10°) to a 1/4° atmosphere for the study of global tropical cyclone and ocean interactions. This coupled model will require the use of an upper ocean wave model to distribute the momentum from the atmosphere to the ocean. The NCEP wave model has been ported to the GFDL Flexible Modeling System (FMS) for it coupling for this purpose.

## 5 Regional modeling

Herzfeld et al. (2010) review features of MOM4p1 facilitating its use for regional modeling. In particular, MOM4p1 has roughly 20 options for open boundary conditions. This range of options allows MOM4p1 to be quite flexible in its regional applications. Additionally, MOM4p1 has a wrapper for the General Ocean Turbulence Model (GOTM) (Umlauf et al., 2005), which is a community turbulence model that provides many options of use for fine resolution regional modeling.

There are three regional applications of MOM4p1 that involve GFDL collaborators. One is the Baltic Sea research effort led by Martin Schmidt in Germany. The second is the Australian regional modeling effort led by Mike Herzfeld at CSIRO in Hobart, Australia. Both of these efforts involve ultra-fine horizontal and vertical grid resolutions (e.g., a few kilometres in the horizontal and finer than a metre in the vertical). Additionally, GFDL has collaborations with Indian scientists to develop a hierarchy of mesoscale eddy permitting regional models for studying Indian Ocean phenomena at the subseasonal to seasonal time scales. These three regional modeling efforts are ocean and ocean-ice models, with no coupling to an atmosphere model.

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