Chapter 1

OGCMs and MRI.COM

This chapter outlines the ocean general circulation models (OGCM) and the status of MRI.COM. See "Organization" in Abstract for an introduction to this manual.

1.1 What do OGCMs cover?

OGCMs have been supposed to simulate relatively large-scale phenomena such as global-scale thermohaline circulations, basin-scale wind-driven circulations, and mesoscale eddies (Figure 1.1). Small-scale processes that are either unresolved or neglected might be incorporated in some forms of subgrid-scale (SGS) parameterizations. The current basin or global scale OGCMs may cover phenomena from thermohaline circulations to mesoscale eddies, but it is still almost impossible to conduct a simulation long enough to achieve a quasi-steady state of a thermohaline circulation with a horizontal resolution ($\sim$ several km) that is sufficiently high to resolve mesoscale eddies, even with the present computation resources. For these reasons, the standard practice in the ocean model community is to use a low horizontal resolution (a few hundred kilometers) model to study global thermohaline circulations and to use a limited-domain model to study an eddying ocean. Some research projects seek to conduct a several-hundred-year integration of a high resolution model that resolves mesoscale eddies using enormous resources, but such a resource is not available to everyone.

In recent years, the OGCMs are used to directly simulate some of the previously unresolved small scale phenomena. These include submesoscale currents (McWilliams, 2016) and the generation of internal gravity waves due to the interactions of tides and mesoscale currents with topographic features. Because large scale features such as mesoscale eddies, boundary currents, and oceanic fronts are prerequisite for the spontaneous emergence of these fine-scale features, an approach of embedding (nesting) subdomains with refined grids in a basin scale model is often taken. Use of a common OGCM code is preferable in these approaches.

1.2 Classification of OGCMs

Most OGCMs used by ocean research scientists and by operational centers for forecasting climate and oceanic states numerically solve almost the same set of equations for the Boussinesq and hydrostatic ocean. The fundamental equations consist of the momentum equation for continuous fluid, the advection-diffusion equation for temperature and salinity, the equation of state of sea water, and the mass conservation equation, collectively called primitive equations (Chapter 2). If necessary, equations for additional processes such as surface mixed-layer physics, sea ice, and bottom boundary layer physics are added.

Most OGCMs applied to ocean-climate studies adopt the finite difference or finite volume method on structured mesh to discretize the equations. Recently, the finite element method on horizontally unstructured mesh is also applied to both coastal ocean simulation and global ocean simulation (e.g., Chen et al., 2011; Danilov, 2013). MRI.COM takes the former approach. The spectral approach widely used by atmospheric models would have difficulty treating lands that completely block ocean circulation in the zonal direction, and thus this approach is not usually adopted in general-purpose ocean models.

Ocean models adopting horizontally structured mesh are classified by how they discretize the vertical direction. The choice of the vertical coordinate leads to fundamental differences among the models. There are three classes: z-coordinate models or z-models adopting depth as the vertical coordinate, σ-coordinate or terrain following models adopting fractional depth between the sea surface and the sea floor as the vertical coordinate, and ρ-coordinate or isopycnal models adopting isentropic surfaces (iso-potential density surfaces) as the vertical coordinate. Each class has its advantages and disadvantages and recent efforts are directed toward adopting generalized vertical coordinates, i.e., remedying each model's disadvantages by using advantages of other classes. Readers are referred to the book by Griffies (2004) for more general discussion about OGCMs.

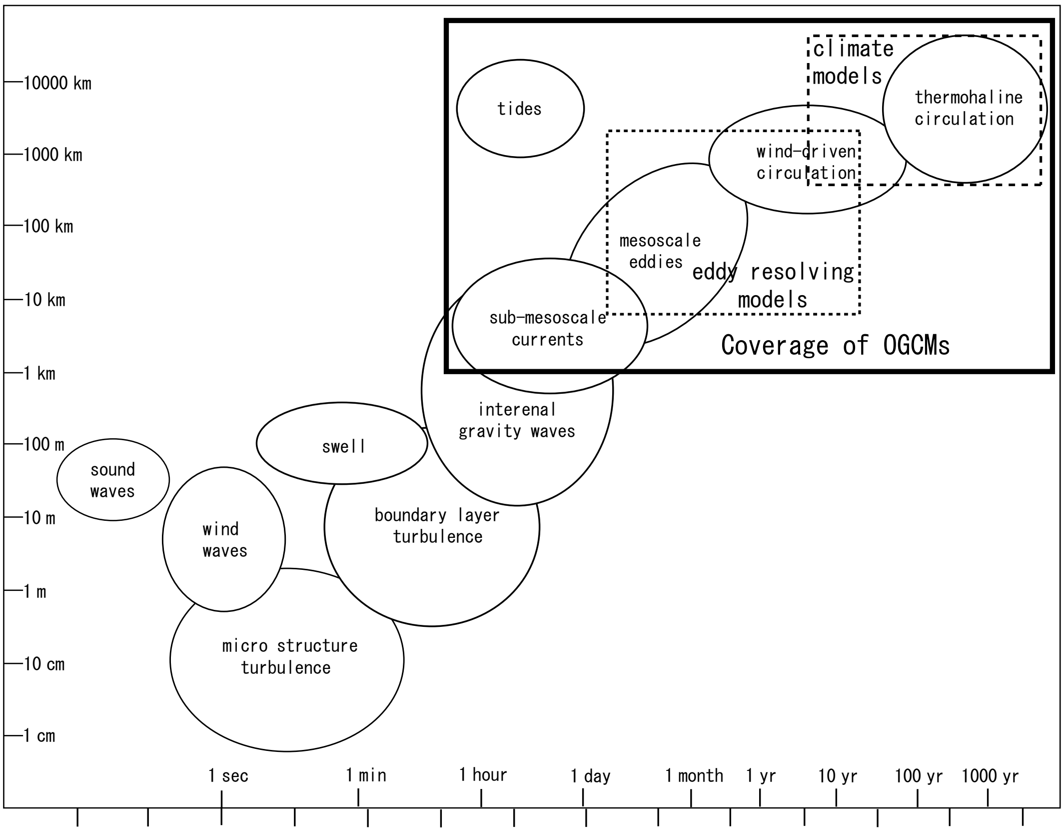

Figure1.1 Various oceanic phenomena in their space and time scales and coverage of the ocean general circulation model. the figure of oceanic phenomena is adopted from von Storch and Zwiers (2001), but some phenomena are added.

1.2.1 Z-coordinate models (z-models)

The first z-coordinate general circulation model was developed by Dr. Kirk Bryan and his colleagues at the Geophysical Fluid Dynamics Laboratory (GFDL) in the 1960's (e.g., Bryan, 1969). This model is sometimes referred to as the Bryan-Cox-Semtner model or GFDL model. The z-models utilize the character of the ocean that the local pressure is expressed as a function of depth by zero-order approximation, which makes implementing the equation of state straightforward. Implementation of bottom topography and drawing of results are also straightforward. The models of this class are most widely used in the community because of their versatility. Such models were first used as components of coupled atmosphere-ocean models.

The descendant of the GFDL model is called the Modular Ocean Model (MOM; Griffies, 2012) and is one of the most widely used z-models. Massachusetts Institute of Technology general circulation model (MITgcm; Marshall et al., 1997) and Nucleus for European Modelling of the Ocean (NEMO; Madec and the NEMO team, 2008) are also widely used. Most climate centers participating in climate model intercomparison projects use the z-coordinate models; MRI.COM also adopts z-coordinate. In Japan, the Center for Climate System Research Ocean Component Model (COCO) at the University of Tokyo (Hasumi, 2006) and the Research Institute of Applied Mechanics Ocean Model (RIAMOM) are also in this class.

The major disadvantages of this class of models are as follows:

- The vertical resolution in shallow seas and near the sea floor tends to be low and the processes that arise near the coast and the sea floor tend to be poorly reproduced.
- Numerical inaccuracy in the tracer transport algorithm immediately leads to spurious diapycnal mixing of the transported properties, while the diapycnal mixing is supposed to be very small in the ideal ocean interior.

The first disadvantage is expected to be remedied by the σ-models and the second by the ρ-models. However, z-model's disadvantages are not completely overcome; these substitutes have their own difficulties.

1.2.2 Sigma-coordinate models (σ-models)

The first sigma-coordinate model was developed by Dr. George Mellor and his colleagues at Princeton University. Since the number of vertical grid points is invariable throughout the model domain, σ-models are widely used for coastal ocean simulations.

Two major sigma-models are widely used in the community: The Princeton Ocean Model (POM; Mellor, 2004) and the Regional Ocean Modeling System (ROMS; Shchepetkin and McWilliams, 2003; 2005).

The major disadvantages of this class of models are as follows:

- An accurate representation of the horizontal pressure gradient is difficult near steeply sloping bottom topography.
- The lateral mixing along the same vertical layer near the continental slope region might lead to mixing of the shoreward light water and the seaward dense water.

These problems might prohibit using σ-models in long-term integrations of the global ocean.

1.2.3 Isopycnal-coordinate models (ρ-models)

The first isopycnal-coordinate model was developed by Dr. Rainer Bleck at the University of Miami. The development of this class of models is based on the fact that sea water moves along isopycnal surfaces in the interior. Thus, the character of a water mass is well maintained in the ocean interior. Since many theoretical studies of physical oceanography use an isopycnal-coordinate framework, the ρ-models have the great advantage of providing good correspondence between theory and numerical models.

A major ρ-model widely used in the community is the Miami Isopycnic Coordinate Ocean Model (MICOM; Bleck and Boudra, 1986) developed at the University of Miami.

The major disadvantages of this class of models are as follows:

- Implementation of surface mixed layer models into a ρ-model is in itself inappropriate.
- Since the density levels are prescribed, this class of models might not be appropriate for studying a drastic climate change that could lead to great variations in density of major water masses.

The Hybrid Coordinate Ocean Model (HYCOM; Bleck et al., 2002) has been developed in an effort to remedy some of these disadvantages.

1.3 About MRI.COM

MRI.COM is a z-coordinate model and uses the finite volume method on structured mesh to discretize the governing equations. The horizontal grid arrangement is Arakawa's B-grid (Arakawa, 1972). Coast lines are defined by the periphery of the grid cell centered by the velocity point, i.e., the lines connecting the tracer points. This arrangement is suitable for the discrete expressions for the side boundary conditions for velocity, and transport through a narrow passage can be achieved with a single grid cell. The time finite-difference scheme has been renewed from Leapfrog + Matsuno scheme to Leapfrog Adams-Moulton (LFAM3), a third-order predictor-corrector scheme, at MRI.COMv5 (Chapter 4).

Though the program code should ideally use MKS units, MRI.COM basically uses cgs units for historical reasons. The sea ice model, the mixed-layer model, some surface bulk formulae, and biogeochemical models are coded in MKS units and converted into cgs units before their outputs are used by the main part. Details are described in each chapter.

1.4 Future of OGCMs and MRI.COM

As OGCMs acquire scientific and numerical integrity, they expand the area of their usage and begin to fulfill social as well as scientific needs. The developer of an OGCM thus has the responsibility to ensure its scientific and numerical integrity and to acknowledge its limitations. Feedback from users of various fields and continuous efforts to overcome limitations will certainly improve the OGCMs.

Innovative ideas are still being published in basic frameworks of OGCMs as well as improvements in various physical schemes. Model development centers around the world continue to improve their OGCMs by incorporating them. For example, the vertical coordinate scheme called the Arbitrary Lagrangian-Eulerian method (ALE), which mixes multiple vertical coordinate systems described in Section 1.2 in a model, has the potential to dramatically improve a long-standing problem of false numerical diffusion. In the development of MRI.COM, we need to keep up with the progress in research about OGCM.

The advance of OGCMs has kept pace with that of super-computers. The mainstream of super computing is shifting from vector computation to massively parallel computation with distributed memory. On the other hand, general-purpose computing using inexpensive Graphics Processing Units (so-called GPGPU) is also becoming widespread in the field of high-performance computing. As the computer architecture advances, our program code must be constantly improved. With increasing computing power, ever higher resolution simulations will be achieved. The result will be more strongly affected by how subgrid-scale processes are parameterized and thus subgrid-scale schemes should be selected carefully.

To continue to stand as a multi-purpose model, an OGCM should be easily coupled with other component models and data assimilation schemes. Other component models include wave, river, iceberg, and ice-shelf models. In the interaction with these models, physical quantities should be exchanged by following conservative lows. Having an interface to universal couplers and an adjoint code should be mandatory for such a multi-purpose OGCM.

These are the main subjects for developing MRI.COM in the coming years.