Applications of the Generalized Vertical Coordinate Ocean Model for Better Representing Satellite Data

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ABSTRACT: ***It is found that two adaptive parametric functions can be introduced into the basic ocean equations for utilizing the optimal or hybrid features of commonly used z-level, terrain-following, isopycnal, and pressure coordinates in numerical ocean models. The two parametric functions are formulated by combining three techniques: the arbitrary vertical coordinate system of Kasahara (1974), the Jacobian pressure gradient formulation of Song (1998), and a newly developed metric factor that permits both compressible (non-Boussinesq) and incompressible (Boussinesq) approximations. Based on the new formulation, an adaptive modeling strategy is proposed and a staggered finite volume method is designed to ensure conservation of important physical properties and numerical accuracy. Implementation of the combined techniques to SCRUM (Song and Haidvogel 1994) shows that the adaptive modeling strategy can be applied to any existing ocean model without incurring computational expense or altering the original numerical schemes. Such a generalized coordinate model is expected to benefit diverse ocean modelers for easily choosing optimal vertical structures and sharing modeling resources based on a common model platform. Several representing oceanographic problems with different scales and characteristics, such as coastal canyons, basin-scale circulation, and global ocean circulation, are used to demonstrate the model's capability for multiple applications. New results show that the model is capable of simultaneously resolving both Boussinesq and non-Boussinesq, and both small- and large-scale processes well. This talk will focus on its applications of multiple satellite sensing data in eddy-resolving simulations of Asian Marginal Sea and Kurosio. Attention will be given to how Topex/Poseidon SSH, TRMM SST, and GRACE ocean bottom pressure can be correctly represented in a non-Boussinesq model.***

KEYWORDS: Numerical Ocean Model, Generalized Coordinate System, Compressible Flow

1. INTRODUCTION

Numerical ocean models have become multi-disciplinary research tools for use in a variety of ocean-related areas, including coupled physical-biogeochemical studies, coupled ocean-atmosphere simulations, and coastal ocean predictions. Due to historical reasons, most of the existing ocean models are built upon a traditional vertical coordinate system, such as the z-coordinate in the Bryan-Cox-Type models (Bryan 1969; Cox 1984), the sigma-coordinate in POM (Blumberg & Mellor 1987), the layer-coordinate in MICOM (Bleck & Chassignet 1994), and the s-coordinate in SCRUM (Song & Haidvogel 1994). Each of these model classes have shown to be advantageous for certain specialized problems, but none of them perform equally well on multi-scale problems because the traditional coordinate systems are not, by themselves, optimal everywhere in the ocean. Recent model-to-model comparison experiments, such as the Dynamics of North Atlantic Models (DYNAMO) and the Data Analysis and Model Evaluation Experiment (DAMEE), has revealed many deficiencies of the present state of ocean modeling and data assimilation (Nowlin 1997). These deficiencies can be summarized as follows:

1. Each model class is based on a single coordinate configuration that limits its ability to be suitable for a wide range of oceanographic applications. Users have no flexibility to choose a desired model structure

beyond the coordinate limitations.

2. Most model features are neither interchangeable nor intercomparable between different model classes. As a result, repetitious and overlapping developments are inevitable among modeling groups.
3. There is little communication and coordination between different model classes. This leads to potential difficulties in implementing nested and coupled ocean models for multi-scale applications.

To overcome these deficiencies, we have developed a generalized vertical coordinate system (Figure 1) as part of the ONR-initiated Expert System. We found that two adaptive parameters could be introduced into the basic ocean equations to generalize all the traditional coordinates into one common model architecture. By choosing these two parameters, a model can be generalized to utilize the optimal or hybrid features of all the traditional coordinate systems, therefore providing a link among all the model classes and offering flexibility for users to choose desired vertical structures for multiple applications.

2. METHODS

Our generalized vertical coordinate system is formulated by combining three techniques - the arbitrary vertical coordinate system of Kasahara (1974), the general pressure gradient formulation of Song (1998), and the newly introduced adaptive parametric function, $\phi = H_z B_z$ - in the basic ocean equations. Here ϕ is the discretized metrics, H_z is the adaptive metric parameter determining the height of the computational layers and B_z is the normalized buoyant parameter permitting compressible (non-Boussinesq or conserving mass) and incompressible (Boussinesq or conserving volume) flow conditions. These two parameters, an extension of the s-coordinate of Song and Haidvogel (1994) and the bottom boundary layer of Song and Chao (2000), are the grid shrink/swallow ratio and water mass/volume ratio, respectively. The former determines the model levels to follow isopycnals, free surface, and bottom topography, while the latter determines the mass or volume between the levels. By choosing the values of the two parameters, a model can be developed to have multiple abilities:

- To enhance the surface layer resolution like the z-coordinate for proper representation of thermodynamical and biogeochemical processes.
- To resolve the bottom boundary layer like the terrain-following coordinate system for studying coastal ocean processes.
- To follow isopycnals in the interior water column like the layer-coordinate system for better maintaining water mass in long-term simulations.
- To permit compressible (non-Boussinesq) flow conditions like the pressure-coordinate for faithful representation of satellite sensing data, such as TOPEX sea-surface data and GRACE bottom pressure anomaly.

3. APPLICATIONS

The generalized vertical coordinate system has been demonstrated based on the S-Coordinate Rutgers University Model (SCRUM). Several well-known problems with different scales and characteristics, such as a coastal canyon, seamount topography, a basin-scale circulation, and a global ocean circulation, are used to test model performance and capability. For simplicity, we present only one of these applications—the wind-driven double-gyre circulation in compressible (non-Boussinesq) flow.

The wind-driven, double-gyre circulation tests the response of the model to wind forcing in a simple geometry and in the absence of any explicit diffusion of density. The wind drives a double-gyre with a western boundary current. The boundary current separates from the wall, which extends far away across the domain and should produce eddies and shed rings. Although it has been modeled by a variety of ocean models (Holland and Haidvogel 1981; Huang et al. 2002), such a problem with eddy-resolving resolution and compressible (non-Boussinesq) flow conditions has not been examined before, to our knowledge. Here we show that our model can be used to solve this problem in both compressible and incompressible flow conditions.

We impose the problem more of a challenge than those of Holland and Haidvogel (1981) by adding a continental slope to the western side of the basin, similar to that used by Song and Wright (1998). Such a varying topography is necessary to test the model's capabilities of representing bottom pressure variations. The computational domain is chosen to be 3600 km by 2800 km in size and divided into an eddy-resolving grid of 181x141 cells. The new generalized pressure-coordinate system is used, in this case, with 20 vertical levels. The driving force is provided by a double-gyre wind stress.

The model had been running prognostically for 8.5 years and the final results - bottom pressure anomaly, surface elevation, velocity, and potential temperature - are shown in Figure 2. As expected, cold cyclonic eddies and warm anticyclonic eddies detach from the south and north sides of the meandering boundary currents. The separation latitude of the western boundary current shifts south of the zero wind stress curl line and a wedge of northern water is advected further southward along the slope. The sloping topography is believed to play a dominant role in the earlier separation of the Gulf Stream due to the joint effect of baroclinicity and relief (JEBAR) as discussed by Song and Wright (1998). This challenging test problem clearly demonstrates the model's capabilities in handling both steep topography and eddy separations in compressible (non-Boussinesq) flow conditions. Such extended capabilities are needed in our community ocean models to faithfully represent satellite-sensing data of TOPEX sea surface elevation and GRACE bottom pressure anomaly (Hughes et al. 2000; Huang et al. 2002).

The model results also show that it is capable of resolving multi-scale processes with both Boussinesq and non-Boussinesq conditions within a single model framework. The generalized vertical coordinate system can be easily implemented into existing ocean models without incurring computational expense or altering the original numerical schemes.

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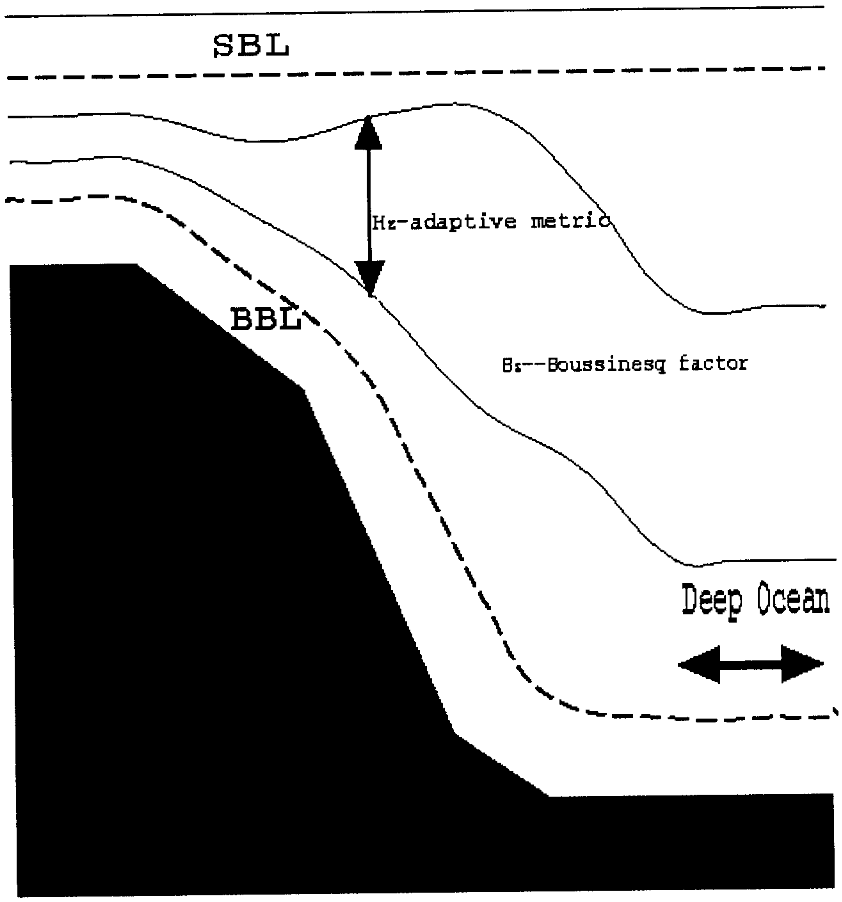

Figure 1. Schematic of the generalized ocean model architecture allowing the combined advantages of different vertical coordinate systems by choosing the two input parameters: adaptive metric and Boussinesq factor.

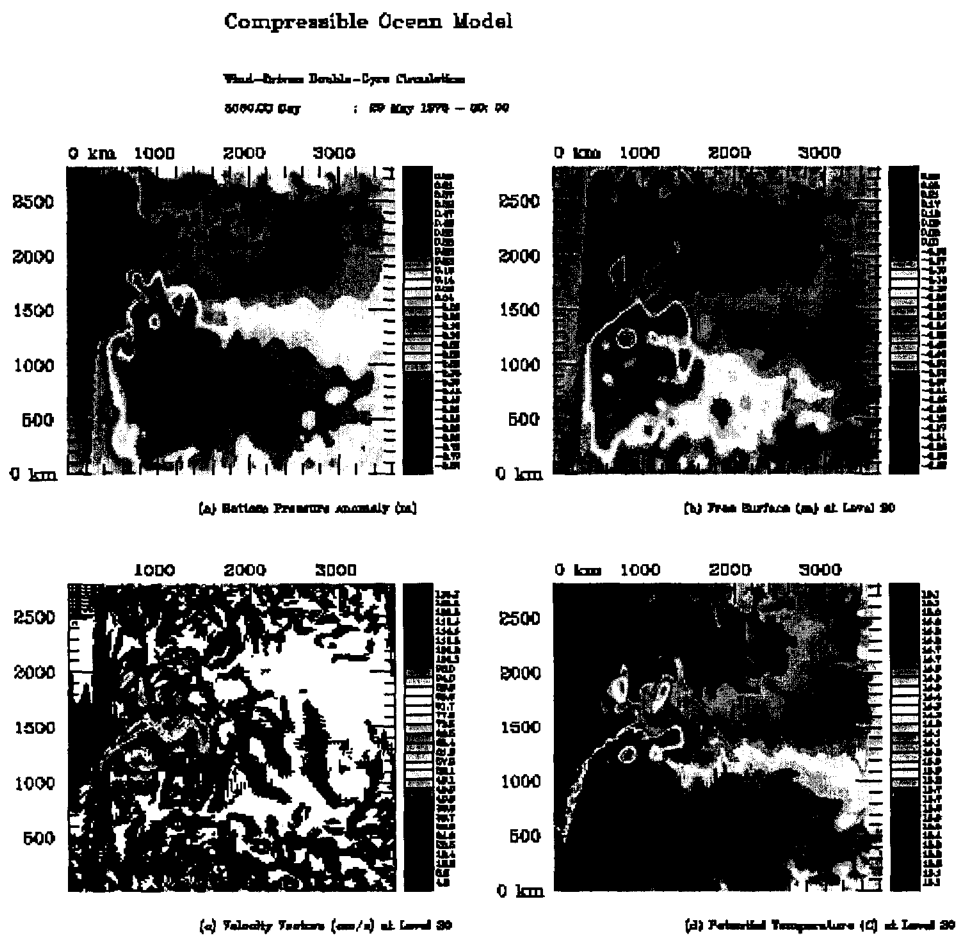

Figure 2. Wind-driven double-gyre simulation at year 8.5: (a) bottom pressure anomaly; (b) free surface elevation; (c) velocity field at the surface layer; and (d) surface temperature. Notice the expected features of eddy shedding from the meandering boundary current and the earlier separation of the "Gulf Stream".