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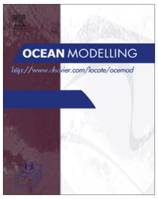

A multi-resolution approach to global ocean modeling

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ABSTRACT

A new global ocean model (MPAS-Ocean) capable of using enhanced resolution in selected regions of the ocean domain is described and evaluated. Three simulations using different grids are presented. The first grid is a uniform high-resolution (15 km) mesh; the second grid has similarly high resolution (15 km) in the North Atlantic (NA), but coarse resolution elsewhere; the third grid is a variable resolution grid like the second but with higher resolution (7.5 km) in the NA. Simulation results are compared to observed sea-surface height (SSH), SSH variance and selected current transports. In general, the simulations produce subtropical and subpolar gyres with peak SSH amplitudes too strong by between 0.25 and 0.40 m. The mesoscale eddy activity within the NA is, in general, well simulated in both structure and amplitude. The uniform high-resolution simulation produces reasonable representations of mesoscale activity throughout the global ocean. Simulations using the second variable-resolution grid are essentially identical to the uniform case within the NA region. The third case with higher NA resolution produces a simulation that agrees somewhat better in the NA with observed SSH, SSH variance and transports than the two 15 km simulations. The actual throughput, including I/O, for the *x1-15 km* simulation is the same as the structured grid Parallel Ocean Program ocean model in its standard high-resolution 0.1° configuration. Our overall conclusion is that this ocean model is a viable candidate for multi-resolution simulations of the global ocean system on climate-change time scales.

1. Introduction

Over the relatively short history of global ocean modeling, the approach has been almost entirely based in structured meshes, conforming quadrilaterals and a desire to obtain quasi-uniform resolution. The first models were situated on a latitude–longitude grid (Bryan, 1969; Cox, 1970; Semtner, 1974) but the grid singularities at the two "grid poles" proved to be problematic. Generalizing the latitude–longitude grid to be a curvilinear grid (Murray and Reason, 2001; Smith et al., 1995) allowed placement of grid poles over land, thus eliminating these singularities from the ocean domain. Since resolution in all regions of these structured, conforming quadrilateral meshes must change in lockstep, doubling resolution requires an additional factor of 10 in computational resources. The ubiquity of this approach is confirmed through the following: all 23 global ocean models used in the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report were based on structured, conforming quadrilateral meshes (see Chapter 8, pg 597 of Randall and Bony, 2007).

Our view is that the global ocean modeling community benefits from having a diversity of numerical approaches. While this diversification is well underway with respect to the modeling of the vertical coordinate (Hallberg, 1997; Bleck, 2002), progress in developing new methods for modeling the horizontal structure of the global ocean on climate-change time scales has lagged behind. New multi-resolution approaches, both structured and unstructured, are emerging with applications focused on regional and coastal ocean modeling (Chen et al., 2003; Danilov et al., 2004; Shchepetkin and McWilliams, 2005; White et al., 2008). The challenges in transitioning from coastal and regional applications to global ocean climate applications is clearly discussed in Griffies et al. (2009). These challenges include the following: lack of robust horizontal discretization, lack of high-order advection algorithms, lack of scale-adaptive (aka scale-aware) physical parameterizations, difficulty in analyzing simulations, and computational expense. We place these challenges into two broad categories: formulation of dynamical core and formulation of scale-adaptive physical parameterizations. The formulation of the dynamical core includes issues related to spatial discretization, temporal discretization, transport and computational expense.

The driving requirements for a dynamical core to be applied in coastal applications can be very different from the requirements for a dynamical core to be used for global ocean climate-change

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applications. While issues related to geostrophic adjustment, tracer conservation, vorticity dynamics and computational efficiency have to be considered early in the formulation of a global ocean dynamical core, these same issues can sometimes be significantly less important for models focused toward coastal applications. As a result, there is tension regarding how to construct an ocean dynamical core capable of bridging spatial scales from coastal to global in a single simulation. Should we start with a coastal model and build "up" or start with a global ocean model and build "down"? We do not think that an answer to this question is known at this time, but our decided preference is to build "down". Essentially, our approach is to construct an ocean dynamical core that, first and foremost, is a viable global ocean model then endow that model with the ability to regionally enhance the grid-scale resolution without degrading the quality of the global simulation.

The model presented below is called MPAS-Ocean. The acronym MPAS represents Model for Prediction Across Scales. MPAS is a set of shared software utilities jointly developed by National Center for Atmospheric Research and Los Alamos National Laboratory for the rapid prototyping of dynamical cores built "on top of" the horizontal discretization developed in Thuburn et al. (2009) and Ringler et al. (2010), along with the variable-resolution Spherical Centroidal Voronoi Tessellations (SCVTs) discussed in Ju et al. (2010). To date, four dynamical cores have been constructed using this framework: a shallow-water model (Ringler et al., 2011), a hydrostatic atmosphere model (Rauscher et al., 2013), a non-hydrostatic atmosphere model (Skamarock et al., 2012), and the ocean model discussed below. A land-ice model similar to Perego et al. (2012) is currently being developed within the MPAS framework. The challenges in creating global, multi-resolution models of the ocean or atmosphere are in many ways similar to those found for coastal models trying to scale up to global domains. Namely, we are challenged to create high-order transport schemes, implement multiscale time stepping algorithms, develop scale-adaptive physical parameterizations and produce new techniques for analyzing simulations.

A global ocean model capable of resolving multiple resolutions within a single simulation must possess the following three properties before such a model will find widespread use in the ocean modeling community. First, as stated above, the ocean model must be competitive with structured-grid global ocean models with respect to physical correctness and simulation quality. Second, the multi-resolution model must be competitive with existing global ocean models with respect to computational cost per degree of freedom. And finally, the dynamics of a multi-resolution ocean simulation as a function of grid-scale must compare favorably to the suite of global uniform simulations that span these same scales. In other words, simulated ocean dynamics should be insensitive to whether that scale is present in a multi-resolution simulation or a quasi-uniform simulation. A global multi-resolution ocean model that possesses these three properties would provide a compelling alternative to existing structured global ocean models. No such compelling alternative exists at present. Furthermore, the results we present below does not warrant us to definitely conclude that MPAS-O possesses any of these properties, but rather the results strongly suggests such properties are obtainable within the MPAS-O approach.

The construction of a new global ocean climate model is a decade-long endeavor. As such, our goal here is not to present a model that is ready for IPCC-class simulations. Our primary goal is to introduce this modeling approach and provide results responsive to the three properties we discuss immediately above. First, we introduce the MPAS approach by summarizing the properties of the conforming mesh and finite-volume method. Second, we provide evidence that the numerical approach has merit as a global, quasi-uniform ocean model through analysis of the current structure and mesoscale eddy characteristics. Third, we show that the mesoscale eddy characteristics and mean-flow conditions of the North Atlantic can be reproduced with a variable resolution ocean model that has high resolution only in the North Atlantic region. And finally, we compare the computational performance of MPAS-O to the LANL Parallel Ocean Program (POP). While a plausible representation of the North Atlantic, obtained with acceptable computational expense, is necessary for the acceptance of a new modeling approach, we realize that such results are far from sufficient. Yet, it seems like a reasonable place to begin. This contribution is entirely focused on the evaluation of the dynamical core and omits almost entirely any discussion of scale-adaptive physical parameterizations. This choice simply reflects the reality that global ocean models are built starting from a dynamical core.

A summary of the simulations discussed in Section 5 provides a sense for our motivation and intended scope. The first simulation, *x1-15 km*, uses a global quasi-uniform (*x1*) grid with a nominal resolution of 15 km. The second simulation, *x5-NA-15 km*, uses a global mesh that varies in resolution by a factor of $\sim$5 (*x5*) with a 15 km resolution in the North Atlantic (*NA*) and 80 km elsewhere. The last simulation, *x5-NA-7.5 km* uses 7.5 km resolution in the NA and approximately 40 km resolution elsewhere. The validity of the modeling approach when configured with a global, quasi-uniform resolution is evaluated by comparing the *x1-15 km* simulation to observational estimates of mean and variance of sea-surface height, as well as analysis of volume transports across well-documented sections. The validity of the multi-resolution modeling approach is evaluated by comparing the *x5-NA-15 km* simulation to the *x1-15 km* simulation in the NA region. While the *x1-15 km* simulation certainly has errors as compared to observations, the error in the multi-resolution approach is measured by comparing a variable resolution simulation to its quasi-uniform counterpart. Therefore, a "perfect" multi-resolution simulation will reproduce both the positive and negative results of its quasi-uniform counterpart within the high-resolution region. The *x5-NA-7.5 km* simulation serves to motivate one potential benefit of this modeling approach as it requires approximately the same computational expense, including the cost of a reduced time step, as the *x1-15 km* simulations, but redistributes the computational degrees of freedom to obtain higher resolution in the NA.

Section 2 provides an overview of the meshes used in this study. More importantly, Section 2 discusses the underlying properties of these meshes that have led us to choose them over more traditional options. Section 3 provides a high-level summary of the numerical approaches used to construct this global ocean model. Since many of these methods are commonly employed in global ocean modeling, the discussion is primarily meant to highlight how this ocean model compares and contrasts with current IPCC-class ocean models. A detailed derivation of the model equations is discussed in Appendix A. Section 4 provides specific details used in the simulations that are then discussed in Section 5. We close in Section 6 with a summary of what has been accomplished with this contribution and what remains to be done.

2. Multi-resolution tessellations of the global ocean

The novel aspect of this contribution is the ability to model the global ocean system using a high-quality, yet easy-to-construct, multi-resolution tessellation (aka mesh or grid). High-quality refers to high local uniformity while multi-resolution refers to the presence of multiple scales. While the attributes of local-uniformity and multi-resolution might seem at odds, the meshes described below have both of these properties. As such, we begin by introducing the relevant aspects of these multi-resolution meshes and describe how such meshes are constructed. While