Scale-Aware Sub-Grid Eddy Parametrizations for Ocean Modeling

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The multi-resolution approach towards global ocean modeling is attractive because it can achieve fine resolutions in regions of interests with manageable computational costs. The success of this approach crucially depends on the access to scale-aware sub-grid eddy parameterizations that can seamlessly transition between different length scales existing on the meshes. Effort is being made to meet this demand, and some initial results are reported here. A scale-aware version of the traditional anticipated potential vorticity method is developed, which can be used on a wide range of multi-resolution meshes without any adjustment of the single non-dimensional parameter needed in the closure. The Gent-McWilliams (GM) closure for mesoscale ocean eddy transport is being studied, and the merits of spatially varying coefficients are evaluated in the context of the Antarctic Circumpolar Current. Results from this study will provide guidelines for the next steps in developing a scale-aware version of the Gent-McWilliams closure.

The ocean plays a critical role in the evolution of our climate system because it is involved in the global water circulation and global heat transfer (e.g., equator-to-pole heat transfer). Through its normal or anomalous behaviors, the ocean also directly affects our human society. For example, the Gulf Stream, which is an intensified western boundary current of the subtropic gyre in the Atlantic, transports warm water from the Gulf of Mexico to the northern Atlantic and produces mild winters in Europe. Hence it is no overstatement that, in order to have a decent understanding of how the climate system works, an accurate representation of the ocean is essential. But the latter has been an extremely challenging task, largely due to the wide range of scales present in the ocean and the nearly inviscid nature of the flow.

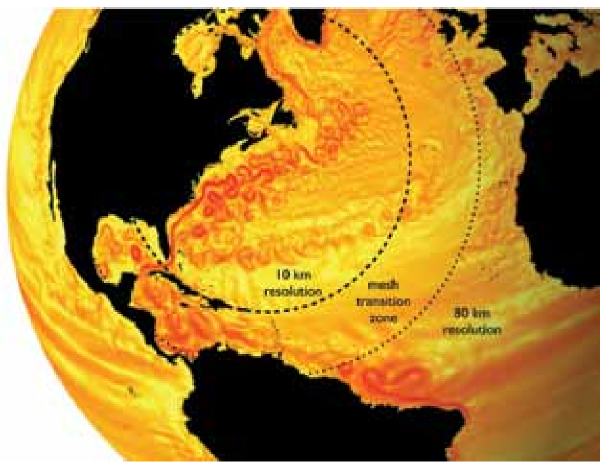

Fig. 1. A snapshot of the kinetic energy on a 10- to 80-km multi-resolution grid. The eddies along the Gulf Stream are fully resolved, thanks to the high resolution in the northern Atlantic.

While unstructured grids have been in use in engineering for many years, the lack of stable numerical schemes suitable for highly rotating geophysical fluid dynamics has precluded adoption of unstructured meshes in the climate community. With unstructured grids, polar singularities that exist on structured grids, such as traditional latitude-longitude grids, are removed, and it is possible to have local refinements on regions of interest and coarse resolutions elsewhere. Model Prediction Across Scales (MPAS) is a joint project between LANL and the National Center for Atmospheric Research (NCAR) to develop finite volume dynamic cores on unstructured grids. Employing the multi-resolution approach, MPAS-Ocean [1] is now able to fully resolve the mesoscale eddies in regions of interest (see Fig. 1), with computational costs that are manageable by today's supercomputers. With local refinements within a global grid, MPAS-Ocean also provides an appealing alternative for regional climate modeling by allowing regional focus within a global simulation.

Mesoscale eddies (30–250 km) play an important role in the ocean dynamics as they facilitate the transport of heat and other tracers. But to date, long-term climate simulations still cannot afford to resolve the mesoscale eddies and they therefore have to be parametrized. Mesoscale eddy parametrization (MEP) is an essential component of all ocean models. Climate models operating on unstructured multi-resolution grids place a new requirement on the development of MEP schemes, namely they should be able to transition smoothly across all the grid lengths existing on the grid–that is, being scale-aware. We endeavor to develop, evaluate, and implement scale-aware MEP schemes for the next-generation climate models.

To explore the methodology, in the first step we study and generalize the Anticipated Potential Vorticity Method (APVM) [2], which is an eddy closure that is perfectly energy conserving and (potential) enstrophy dissipating. The traditional APVM involves a coefficient that depends on a parameter usually taken as a constant in applications. We employ the 2D isotropic turbulence theory and derive a new formulation for the APVM coefficient that depends on a single scale-invariant parameter. The new formulation is tested in an idealized shallow-water model, first on quasi-uniform unstructured grids [3], and then on variable-resolution

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Funding Acknowledgments
DOE, Office of Science, Adavanced Scientific Computing Research Program, Computational Science Research and Partnership (SciDAC); BER, Regional Climate Modeling Project

unstructured grids [4]. Figure 2 can best demonstrate the scale-aware property of the new formulation. It contains plots of the potential enstrophy (PE–the variance of the potential vorticity) spectral density curves, generated with an empirically determined optimal value for the single parameter of the new formulation, on a set of variable-resolution grids. For each of these variable-resolution grids, the new formulation of the APVM is able to produce a PE spectrum curve that is close to the reference spectrum curve across the entire inertial range. This shows that the new formulation is scale-aware, and robust in the sense that the optimal value for the parameter determined on one grid can be satisfactorily used on other grids as well.

Taking one step forward, we study the GM closure [5,6]. GM is a closure of the mesoscale eddy transport of passive tracers. It is an essential component of almost every ocean model out there, and it is hard to over-estimate the role it has played in ocean modeling. GM is based on the fundamental assumption that eddy transport of tracers should be down the thickness gradient and along, not across, the isopycnal surfaces. The GM closure is far more physically relevant and far more complex than APVM. A scale-aware version of GM, assuming it exists, will necessarily exhibit non-uniformity in space and be attuned to the baroclinic instabilities. We begin our study of GM by seeking answers to the preliminary but important question of whether using spatially varying eddy diffusivities can lead to improved results [7]. We approach this question with a set of controlled simulations using a three-layer isopycnal model of the Antarctic Circumpolar Current (ACC). In this study we take the most direct approach by deriving the eddy diffusivities from a high-resolution reference simulation and then feeding the derived diffusivities to low-resolution simulations. The results demonstrate that using spatially varying eddy diffusivities remedies the major deficiency of the extended GM closure [8]. It also leads to improved results with regard to the thickness and potential vorticity (PV) profiles and the volume fluxes. Results from this study will provide guidelines in developing a spatially varying GM coefficient and ultimately a scale-aware version of the GM closure.

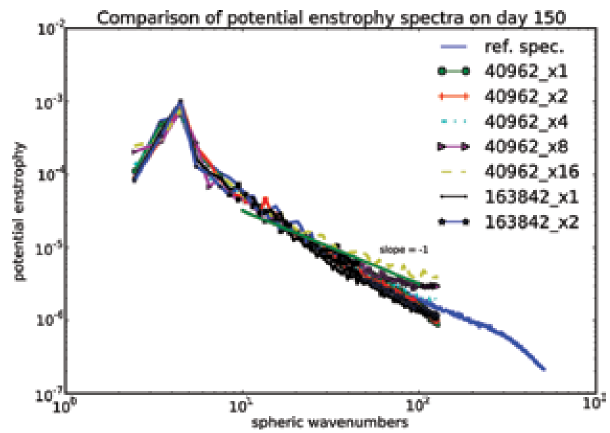

Fig. 2. The potential enstrophy spectrum curves generated by a single value (0.0020) for the APVM parameter on a set of multi-resolution grids. In the grid designation n1_×n2, n1 denotes the number of grid cells, and n2 denotes the ratio between the coarsest and finest resolutions, which can be up to 16 for our study.

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