Seamless Multiscale Forecasting: Hybridizable Unstructured-mesh Modeling and Conservative Two-way Nesting

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LONG-TERM GOALS

Our long-term goal is to *improve, utilize, and verify: (i) HYCOM-downscaling schemes and conservative two-way nesting schemes for seamless multiscale forecasting and dynamical analyses of realistic coupled physics at abrupt topography, and, (ii) High-order non-hydrostatic HDG schemes for high-fidelity, conservative, and efficient multi-dynamics modeling.*

OBJECTIVES

Our specific objectives for the present NOPP project are to:

- Set-up, improve and utilize our schemes for downscaling, conservative implicit two-way nesting, nested and open boundary conditions, and adaptive generalized vertical coordinates, so as to allow efficient multi-resolution modeling
- Improve and utilize our high-order Hybridizable Discontinuous Galerkin (HDG) code to complete process modeling studies relevant to flows encountering abrupt topography including shelf physics, steep shelfbreak dynamics and non-hydrostatics physics in shallow and deep waters.
- Contribute to real-time forecasting and data-assimilative simulations for FLEAT and for inputs to acoustics modeling and coupled simulations
- Perform multi-resolution re-analyses, process studies and multiscale dynamics analyses focusing on interactions of currents and circulation features with topographic waves, internal tides or bottom gravity currents
- Collaborate with NOPP team and NRL, transferring approaches, algorithms and simulations. Utilize the MIT Naval Officer education program.

APPROACH

One of our research goals is to derive and apply advanced techniques for multiscale modeling of tidal-to-mesoscale processes over regional domains (nearshore-coastal-basin) with complex geometries including shallow seas with strong tides, steep shelfbreaks with fronts, and deep ocean interactions. On the one hand, our conservative implicit two-way nesting for realistic multi-resolution modeling has enabled such high-fidelity coupled multiscale dynamics studies. On the other hand, a high-order multi-dynamics modeling capability based on novel hybridizable discontinuous Galerkin (HDG) numerical schemes is also promising for seamless conservative multi-resolution forecasting. Our goal for this NOPP project is to improve, utilize and verify: (i) HYCOM downscaling schemes and conservative two-way nesting schemes for seamless multiscale forecasting and dynamical analyses of realistic coupled physics at abrupt topography; and, (ii) high-order non-hydrostatic HDG schemes for high-fidelity, conservative, and efficient multi-dynamics modeling.

HYCOM downscaling and conservative two-way nesting for seamless multiscale forecasting. We plan to apply and further develop our downscaling and two-way nesting schemes for domains with abrupt topography in the West Pacific Ridge ocean region. For the downscaling and merging of varied modeling and observation inputs at initialization, we will utilize our new semi-analytical optimized initialization and downscaling methodology. Our implicit two-way nesting will aim for seamless and numerical-bias-free nesting of multiscale dynamics, from internal tides to larger-scale dynamics. We plan to evaluate the sensitivity to the HYCOM inputs and to the parameters of the two-way nesting. We will refine nested-grid boundary conditions and conservative multi-grid exchanges such that upscale and downscale effects of multiple dynamics, from nonlinear internal tides to basin-scale currents, are transferred accurately across the multi-resolution domains. We intend to continue our implementation of generalized adaptive vertical coordinate systems. We plan to contribute to real-time forecasting and data-assimilative simulations for the FLEAT observation region and for inputs to acoustics modeling and coupled simulations. We also plan to perform multi-resolution re-analyses, process studies and multiscale dynamics analyses focusing on interactions of current systems and circulation features with topographic waves, internal tides or bottom gravity currents.

High-order non-hydrostatic HDG schemes for high-fidelity multi-dynamics modeling. We plan to improve and utilize our HDG finite-element code to complete process modeling studies relevant to flows encountering abrupt topography. To do so, we will further develop the HDG schemes and their efficient implementation. The schemes combine the HDG method with a projection method and selective slope limiting to obtain high-order accurate schemes for non-hydrostatic ocean flows with a nonlinear free surface. After downscaling from HYCOM, we plan to research and implement our HDG finite-element schemes such that they can run with multiple dynamics within the same computational domain. With parallel computing, our HDG scheme then solve these sets of elements with different dynamics on different compute nodes. The dynamical goal for the high-order HDG simulations is to allow process modeling studies of flows encountering abrupt topography, especially multiscale phenomena that involve shelf physics, steep shelfbreak dynamics and non-hydrostatics physics in shallow and deep waters.

WORK COMPLETED

HYCOM downscaling and conservative two-way nesting for seamless multiscale forecasting. We further developed and applied our downscaling initialization methodology based on a least-square best-fit of the higher-resolution fields to the coarser resolution fields. The least-square (or in general Bayesian estimation) approach is effective since the islands, the bathymetry, and also the dynamics are not the same at the two resolutions. It was applied in several ocean regions (see Figures 1 and 2) to evaluate robustness. We are also improving our two-way nesting and tilling procedures (Figure 3), focusing on the two time-step implementations, a short time-step for the free surface and barotropic velocity, and a longer time-step for the other variables. We have also developed a methodology to define telescoping grids which allow successful communication of field data between resolutions, while maintaining fidelity to the more stringent of the topographic conditions.

High-order non-hydrostatic HDG schemes for high-fidelity multi-dynamics modeling. We have improved our hybridizable discontinuous Galerkin (HDG) finite element code and utilized it in non-hydrostatic, oscillatory flow configurations that encounter abrupt topographic features, generating internal tides/waves, or internal solitary waves (Figure 4). For cases where internal tides/waves are generated, we investigated the effect of bottom boundary and boundary condition configurations, local stabilization parameters, discretization order, and the initialization procedure. For cases where solitary waves are generated, we have studied the sensitivity of the model to the tidal amplitude, period, and, briefly, limiter selectivity criterion and reference spectra decay rates for the filter. We have also compared the behavior and performance of several schemes for handling the singular linear system associated with the pressure corrector used in our projection method employed by the HDG code.

RESULTS

HYCOM downscaling and conservative two-way nesting for seamless multiscale forecasting. We have successfully applied our downscaling procedures on HYCOM output fields for higher resolution telescoping simulations with our MSEAS primitive-equation modeling system. Such examples are shown on Figure 1, specifically the: western Pacific (Fig. 1a), Bay of Bengal (Fig. 1b), western North Atlantic (Fig. 1c), and Bismarck Sea (Fig. 1d). The effects of our optimized downscaling are illustrated on Figure 2. We have applied our two-way nesting and tilling schemes to the West Pacific Ridge, resulting in the tiling configuration shown in Figure 3. Higher-resolution domains have been used around Palau, Guam, and Yap, where very steep topography is present east of these islands.

High-order non-hydrostatic HDG schemes for high-fidelity multi-dynamics modeling. We have tested our improved HDG code in several idealized flow environments for flow over an isolated, shallow, but abrupt sea mount. The code successfully generated internal wave beams with the correct (non-hydrostatic) ray angle (see Figure 4a). In these situations, the choice of bottom BCs, stabilization parameters, and use of higher-order discretization had a critical effect on solution quality. We also found that a penalization scheme was most computationally efficient for handling the singular linear pressure system while also maintaining accuracy of the pressure field; other schemes tried were either prohibitively expensive or degraded the solution. Finally, we also tested the capability of the HDG approach to generate nonlinear solitary waves. One example (Figure 4b) focused on the combination of steep bathymetry and tidal forcing of a stratified density field to locally generate internal tides that can steepen to form nonlinear solitary waves.

IMPACT/APPLICATIONS

Our developments of multi-dynamics downscaling schemes, of conservative two-way nesting for seamless multiscale forecasting, and of high-order non-hydrostatic HDG schemes for high-fidelity modeling are critical to modernize today's and enhance future naval operations. These new methods and schemes are employed for high fidelity data-assimilative multi-resolution modeling of flows in regions with abrupt topography. Our collaborative research will improve the understanding of how such topographic interactions influence the structure of major current systems, generate internal waves and affect internal wave climates, and lead to vigorous unstable bottom gravity currents. It will also improve ocean forecasting and impact acoustic performance forecasting in such steep topography regions. Overall, our proposed integration of research areas in several disciplines such as computational fluid dynamics, multi-resolution ocean modeling, nonlinear estimation, stochastic modeling, ocean observing and prediction systems, and distributed computing is directly applicable to the naval needs of this new century.

TRANSITIONS AND COLLABORATIONS

We have started to discuss collaborations with the other scientists involved in the NOPP project, including HYCOM representatives, with a focus on optimized high-resolution telescoping downscaling and 2-way nesting with tides.

RELATED PROJECTS

Our DRI-FLEAT project on “High-Order Multi-Resolution Multi-Dynamics Modeling for FLEAT” (N00014-15-1-2626) benefits from, and contributes to, the present study.

FIGURES

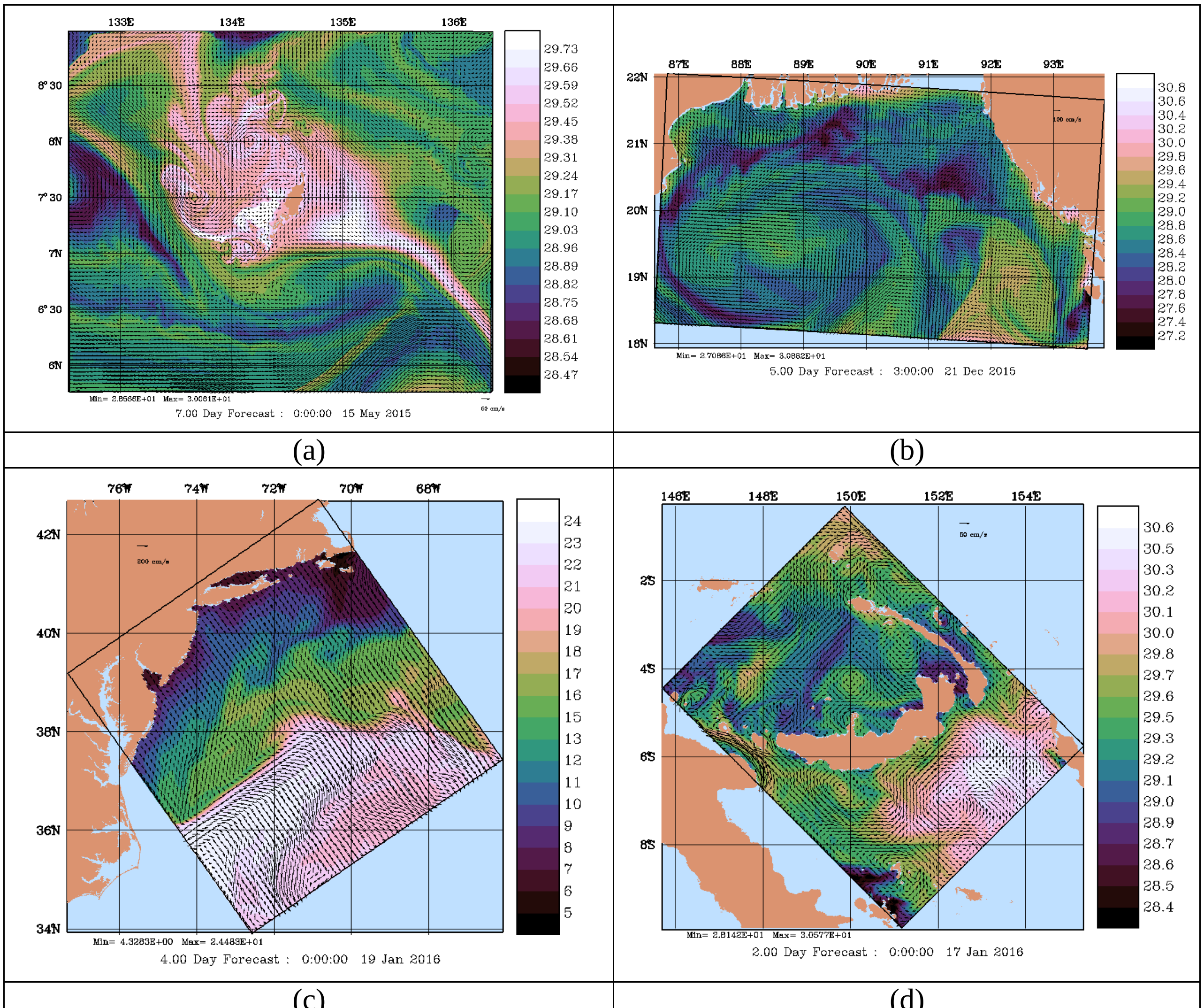

Figure 1. Downscaling HYCOM fields to our MSEAS primitive-equation modeling system for higher resolution (1/75 to 1/675 deg.) tidal-to-mesoscale simulations in various regions. The downscaled sea surface temperature and velocity are shown for the (a) western Pacific around Palau, (b) Bay of Bengal, (c) western North Atlantic off of the US coast, and (d) Bismarck Sea around New Britain.

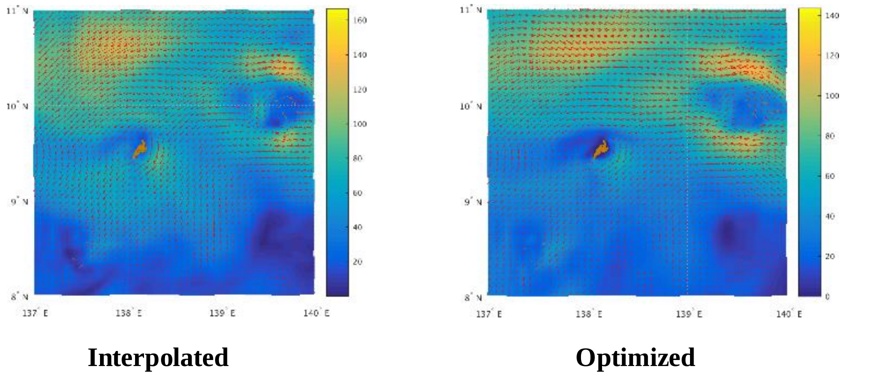

Figure 2. Optimizing velocities and transports for complex multiply-connected regions with multiscale dynamics.

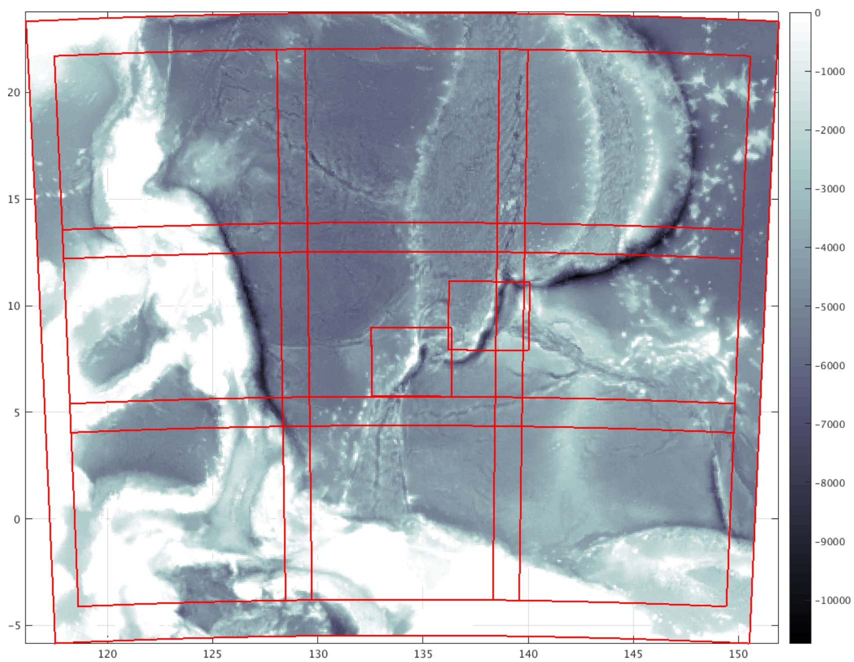

Figure 3. Domain tiling over the West Pacific Ridge, used in our two-way nested schemes. Smaller, higher-resolution domains are used around Palau and Yap.

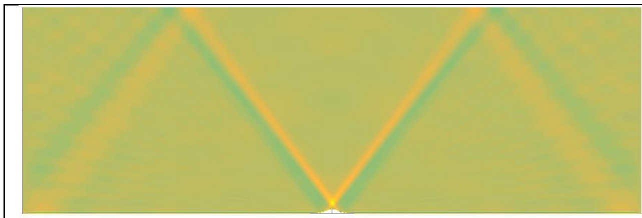

Figure 4a. HDG high-order finite-element non-hydrostatic simulations of internal waves in the horizontal velocity profile after 15.25 cycles of tidal forcing, in the presence of a shallow, abrupt sea mount. Flow snapshot is left to right.

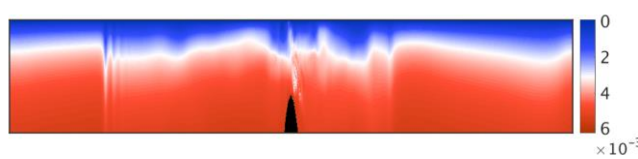

Figure 4b. HDG high-order finite-element non-hydrostatic simulation of solitons created at steep critical ridges in a stratified density field.