U.S. DEPARTMENT OF ENERGY | Office of Science

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FY 2018 Second Quarter Performance Metric: Demonstrate ability to replicate uniform-mesh high-resolution simulation quality using local mesh refinement in test-case or global-ocean configurations

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DISCLAIMER

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1.0 Product Definition

High-fidelity simulations of the Earth System depend critically on an accurate representation of global ocean currents and their eddies. Earth System Model (ESM) simulations that do not include ocean mesoscale eddy variability have been shown to have numerous biases, including: inaccurate sea surface temperatures (Delworth et al. 2011), weaker meridional heat transport (Kirtman et al. 2012), inaccurate strength and location of western boundary currents (Kirtman et al. 2012, McClean et al. 2011), and poorly represented coastal upwelling (Small et al. 2014). In order to simulate ocean mesoscale eddy variability, an ocean model must resolve the characteristic length scale of mesoscale eddies, referred to as the first Rossby radius of deformation (RRD; Chelton et al. 1998). The quality of eddies produced at different resolutions with respect to the RRD demonstrates the ability of the model to reproduce mesoscale eddy mixing, which is essential for transport of heat, freshwater, and biogeochemical constituents into the global ocean (Dutay et al. 2002, Gnanadesikan et al. 2004, Siegenthaler 1983).

A common way to assess the capability of an ocean model to produce an accurate eddy climate is via the classic eddying-double gyre benchmark (Berloff et al. 2002, Figueroa & Olson 1994, Holland & Lin 1975, Poje & Haller 1999, Straub & Nadiga 2014). The *Simulating Ocean Mesoscale Activity* (SOMA) test case (Wolfram et al. 2015) mimics a strongly eddying-double gyre similar to the North Atlantic Gulf Stream. Here, the SOMA benchmark is used to investigate the ability of local mesh refinement to resolve the eddy climate relative to a uniform, high-resolution-mesh simulation.

A high-fidelity capability for simulating eddies with a variable-resolution ocean is demonstrated in the DOE-ocean model, as validated against the SOMA benchmark

2.0 Product Documentation

The ocean component of the U.S. Department of Energy (DOE)'s Energy Exascale Earth System Model (E3SM) is the *Model for Prediction Across Scale - Ocean* (MPAS-O; Ringler et al. 2013). A new variable-resolution-mesh configuration of MPAS-O has been used for the SOMA test case to understand the capability of local mesh refinement to resolve a strongly eddying ocean climate. SOMA has been configured in MPAS-O at a uniform high resolution of 4km, as in Wolfram et al. (2015), and with variable-resolution using local mesh refinement ranging from 32 to 4km (herein). Here we assess the accuracy of the variable-resolution-mesh approach relative to the uniform, high-resolution approach.

MPAS-O's ability to simulate mesoscale eddy variability using local mesh refinement and to produce a solution with the fidelity of uniform high resolution provides confidence that E3SM can provide improved ocean simulations at lower computational cost. Below, we assess SOMA simulation fidelity both qualitatively (by visual inspection) and quantitatively, using the coefficient of determination r^2 (Crow et al. 1960).

3.0 Results

The SOMA benchmark (Figure 1) is derived from a standard test case of ocean model eddying capabilities forced by a steady zonal wind (Berloff et al. 2002, Figueroa & Olson 1994, Holland & Lin 1975, Poje & Haller 1999, Straub & Nadiga 2014, Wolfram et al. 2015).

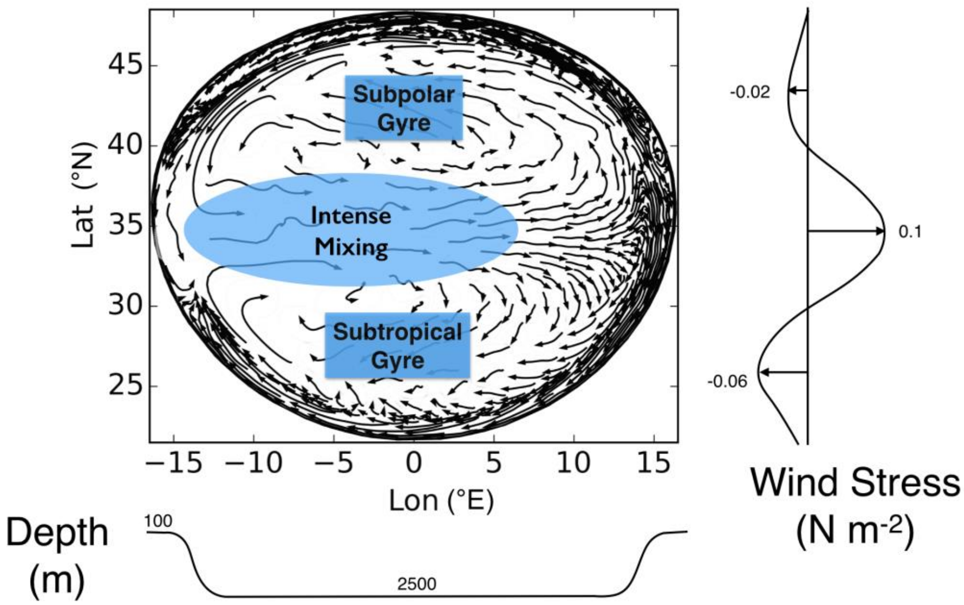

Figure 1. Overview of the wind-forced SOMA benchmark model configuration. Basin bathymetry depth and wind forcing is shown. Average flow vectors in the basin (in black) are shown to highlight the subpolar and subtropical large-scale ocean gyre flows and region of intense mixing in the baroclinic jet between the gyres.

SOMA is initialized from a stratified ocean to approximate the observed pre-existing vertical structure of the ocean. Because eddy production occurs on short time scales, the simulation is spun-up from rest to a quasi-equilibrium state prior to assessment of the eddy climate. Steady zonal wind forcing is applied for five years, to equilibrate the eddy climate, after which the simulation is integrated for another five years while the sea surface height and eddy climatology analysis takes place (Wolfram et al. 2015).

The SOMA benchmark assesses a model's ability to accurately simulate the generation of mesoscale eddies by baroclinic instability, which converts potential energy stored in ocean stratification to kinetic energy via eddies. Baroclinic instability occurs at length scales on the order of the Rossby Radius of Deformation (RRD). Thus, the RRD constrains the size of eddies produced in the SOMA simulation (Vallis 2017). Enhanced resolution is needed to resolve this scale and ensure that eddies are properly simulated.

The characteristic RRD of the idealized mid-latitude SOMA basin is approximately 32km (Wolfram et al. 2015) and the uniform, high-resolution mesh for MPAS-O is approximately 4km, a factor of eight times smaller than the RRD. This high-resolution mesh is well resolved and able to adequately simulate mixing by the eddies (Wolfram et al. 2015). The flow leads to two zonally oriented, counter-rotating, large-scale ocean currents that produce a subpolar gyre, a subtropical gyre, and a baroclinic jet corresponding to a region of enhanced eddy activity (between the gyres at 35^{o} N, as shown in Figure 1).

The local mesh refinement case uses 4km resolution in the western baroclinic jet to resolve the enhanced eddy activity at the interface between the subpolar and subtropical gyres. A lower mesh resolution of 32km is used in the east (Figure 2). The locally refined configuration is expected to fully resolve mesoscale eddy activity in the baroclinic jet and marginally resolve it away from the jet. Here, the computational benefit of local mesh refinement is a computational savings of approximately 70%, via fewer simulated degrees of freedom.

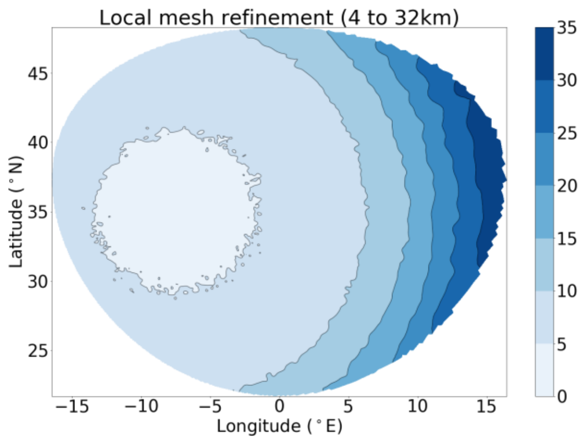

Figure 2. Variable-resolution mesh (color scale, in km) for the 4 to 32km SOMA configuration.

Quantitative assessment of SOMA's climate when using the variable-resolution mesh is performed using the coefficient of determination r^2. The comparison is made by linearly interpolating the variable-resolution mesh results onto the uniform, high-resolution mesh.

The MPAS-O SOMA configuration using local mesh refinement (Figure 2) can accurately reproduce the mean sea surface height (SSH) climate of the uniform high-resolution SOMA configuration (Figure 3), which is composed of a subpolar region of decreased sea surface height to the north of 35° N corresponding to the large-scale, counter-clockwise current. Likewise, the large-scale, clockwise current to the south of 35° N is accompanied by a region of elevated mean sea level. The simulation of mean sea surface height with the variable-resolution mesh captures 98% of the variability represented by the uniform-mesh resolution (r^2 = 0.98).

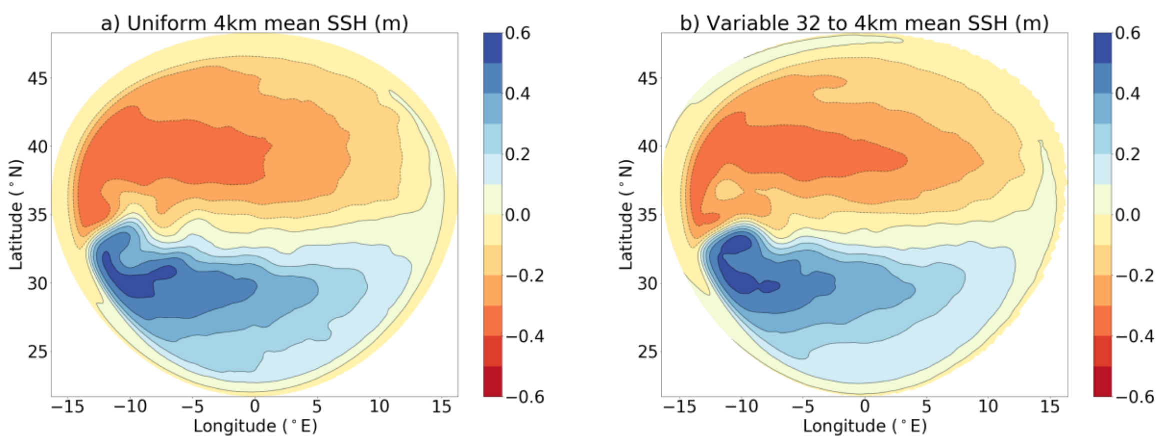

Figure 3. Mean sea surface height (SSH, m) from (a) uniform, high-resolution (4km) SOMA configuration and (b) from a local mesh refinement (4 to 32km) SOMA configuration.

Strong eddy activity occurs at the interface between these large-scale currents and is quantified using the magnitude and structure of the sea surface height standard deviation as well as the eddy kinetic energy. The standard deviation of sea surface height is comparable between the uniform and variable-resolution meshes (r^2=0.95, Figure 4).

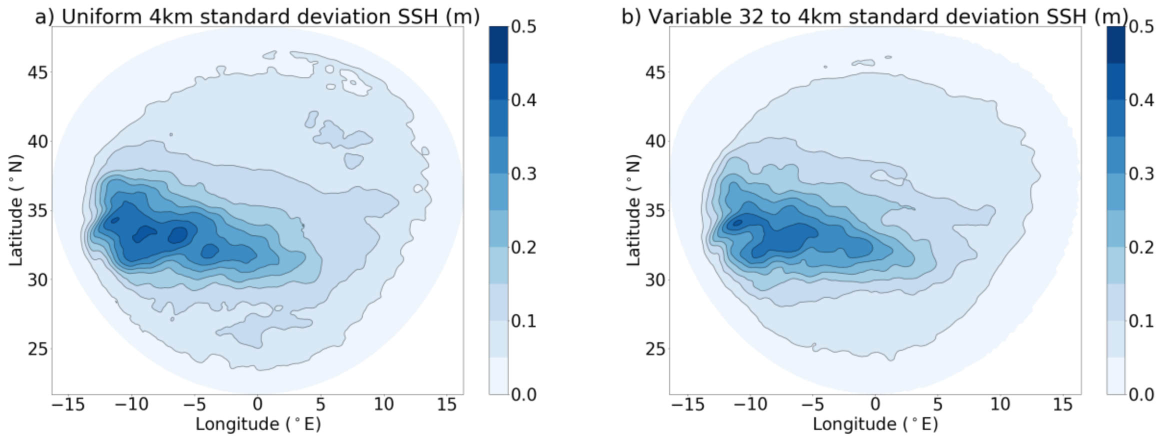

Figure 4. Standard deviation of sea surface height (SSH, m) from (a) the uniform high-resolution (4km) SOMA configuration and (b) the local mesh refinement (4 to 32km) SOMA configuration.

Similar to variability in sea surface height, the eddy kinetic energy is well represented in the locally refined configuration (r^2=0.95, Figure 5). The high-quality, variable-resolution solution gives confidence that local mesh refinement is able to adequately reproduce mesoscale eddies.

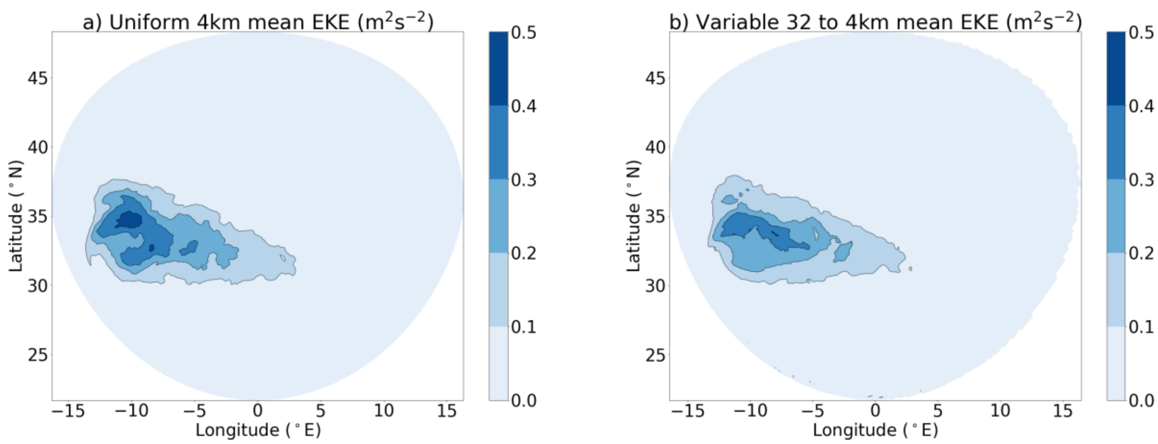

Figure 5. Mean eddy kinetic energy (EKE, m^2s^{-2}) from (a) the uniform high-resolution (4km) SOMA configuration and (b) the local mesh refinement (4 to 32km) SOMA configuration.

In summary, MPAS-O is able to resolve mesoscale activity for the SOMA configuration. The locally refined mesh produces a comparable solution to the uniform, high-resolution mesh, both qualitatively and quantitatively ($r^2 \geq 0.95$ for all standard metrics compared here). Furthermore, a global simulation for the *Coordinated Ocean-ice Reference Experiment* (CORE, Large & Yeager 2004) with local mesh refinement in the North Atlantic was shown to be comparable to a uniform mesh solution (see Ringler et al. 2013, Figures 8-10 therein). These idealistic and realistic simulations demonstrate that simulation quality using a uniform, high-resolution mesh can be replicated with local mesh refinement. This local mesh refinement capability will enable MPAS-O and E3SM to facilitate novel science applications, such as ocean and land-ice interactions, resolution of boundary and coastal currents, and assessment of regional sea level rise and its associated ocean-land interactions.

4.0 References

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