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U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2018 First Quarter Performance Metric: Demonstrate mesoscale ocean simulation success by comparing sea-surface height variability in high-resolution E3SM-MPAS-Ocean to satellite-derived observations

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Contents

Figures

1.0 Product Definition

High-fidelity simulations of the Earth System depend critically on an accurate representation of global ocean currents. Earth System Models (ESMs) in which the simulated currents do not include ocean mesoscale eddy variability have been shown to have numerous biases, including: inaccurate sea surface temperatures (Delworth et al. 2012), 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). A new high-resolution configuration of the ocean and sea-ice components of DOE's E3SM has been implemented and used in a simulation forced by the CORE v2 interannual forcing data set (Large and Yeager, 2009). The ocean component of E3SM is the Model for Prediction Across Scale - Ocean (MPAS-O). This configuration is validated by comparing the simulated sea-surface height (SSH) variability to satellite-derived SSH variability from the AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic) data set.

2.0 Product Documentation

In order to simulate ocean mesoscale eddy variability, the 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 E3SM ocean and sea-ice components have been configured to fully resolve the RRD throughout the vast majority of the ocean. Near the Equator the horizontal grid resolution of the high-resolution E3SM ocean model is 18 km and near the poles the resolution increases to 6 km. This configuration is expected to fully resolve mesoscale eddy activity in most of the global ocean and is similar to 0.1o resolution in traditional-gridded ocean models (e.g., Maltrud and McClean, 2005; McClean et al. 2011, Kirtman et al. 2012). Unlike previous high-resolution ocean simulations, the E3SM high-resolution configuration also fully resolves the first RRD in the vertical direction as well. Stewart et al. (2017) show that an improved representation of mesoscale eddies in the vertical increases SSH variability, eddy kinetic energy (EKE), and the magnitude of the meridional overturning circulation. The vertical-grid-generation algorithm of Stewart et al. (2017) was used to generate the MPAS-O grid for the E3SM high-resolution configuration. The resulting 80-layer vertical coordinate has a characteristic resolution of 2m in the top layer expanding to 90 m at ~1 km depth.

The AVISO satellite has measured SSH variability for more than 20 years. The observations are also at a high enough spatial resolution (0.25o × 0.25o) to compare directly to high-resolution simulations. The standard deviation of SSH from E3SM is compared with AVISO observations in Figure 1. In general, E3SM SSH variability compares well to AVISO.

3.0 Results

High-fidelity simulations of the Earth System are critically dependent on the accuracy of the model's representation of oceanic flows. Earth System Models (ESMs) with an ocean component that resolves mesoscale eddies have been shown to have smaller biases in numerous important metrics than models in which these eddies are either partially resolved or completely absent. These improvements are observed in both the mean state of the ocean and its temporal variability. Delworth et al. (2012), using the GFDL climate model, finds that higher resolution alone is enough to reduce SST biases in the coupled system.

Further, increasing ocean model resolution from eddy permitting (~0.25o) to eddy resolving (0.1o) reduces subsurface temperature anomalies in coupled simulations (Delworth et al. 2012). Increased ocean resolution in an ESM increases North Atlantic meridional heat transport and the strength of the meridional overturning circulation (MOC), possibly due to improving the resolution of small-scale currents (Kirtman et al. 2012).

Accurate representation of eddy mesoscale activity, and in particular its variability, has been shown to reduce biases in western boundary currents (Delworth et al. 2012; Kirtman et al. 2012). As an example, at low ocean-model resolution, the modeled Gulf Stream does not separate from the eastern coast of the United States, contrary to observations, but at higher resolution the modeled Gulf Stream separates near Cape Hatteras, North Carolina as observed.

Given the relative paucity of ocean observations, validation of global ocean models can be difficult, especially in the case of eddy activity. Ship cruises, moorings, and Argo floats, though highly useful for determining the mean ocean state, are not typically appropriate for capturing eddy dynamics. Fortunately, a subset of oceanic satellite observations has fine enough spatial and temporal resolution and a long enough data record to be used for validation of surface mesoscale eddy activity. Among the oceanic satellite observations, sea-surface height (SSH) is most commonly used (e.g., Ducet et al. 2000, Maltrud and McClean, 2005, Kirtman et al. 2012, Delworth et al. 2012).

Figure 1 shows a comparison between E3SM high resolution and AVISO. The SSH variability simulated by E3SM is consistent with AVISO, with a spatial pattern of strong variability associated with western boundary currents clearly visible in both model output and observations. One minor deviation from observations is in the Agulhas region, where the path of mesoscale eddies shed from the Agulhas current is far too regular in E3SM. This can be seen as a “finger” of high SSH variability pointing northwest from the Cape of Good Hope, which is not seen in AVISO. We also note that in E3SM the background variability is higher. This is likely due to the use of high-frequency snapshots in E3SM, which does not filter the SSH variability associated with high-frequency surface gravity wave activity. The influence of gravity waves and tides have been explicitly removed from the AVISO data set.

The high-resolution configuration of the ocean and sea-ice components of E3SM is forced by the CORE v2 interannual forcing data set (Large and Yeager, 2009). Unlike previous high-resolution ocean simulations, the E3SM high-resolution configuration fully resolves the first Rossby radius of deformation in the vast majority of the global ocean in not only the horizontal but also the vertical dimension. Stewart et al. (2017) shows that an improved representation of mesoscale eddies in the vertical increases SSH variability, eddy kinetic energy (EKE), and the magnitude of the meridional overturning circulation (MOC). The vertical –grid-generation algorithm of Stewart et al. (2017) was used to generate the MPAS-O grid for the E3SM high-resolution configuration. The resulting 80-layer vertical coordinate has a characteristic resolution of 2m in the top layer expanding to 90 m at ~1 km depth.

In Figure 2, we show the averaged vertical profile of the MOC at 26.5oN for high- and low-resolution configurations of E3SM. At low-resolution, the modeled MOC falls below the observed strength and range of variability of the observed MOC. When the horizontal resolution of the ocean model is increased, the model representation of the MOC greatly improves (consistent with Stewart et al. 2017) and at most depths falls within the range of observational variability.

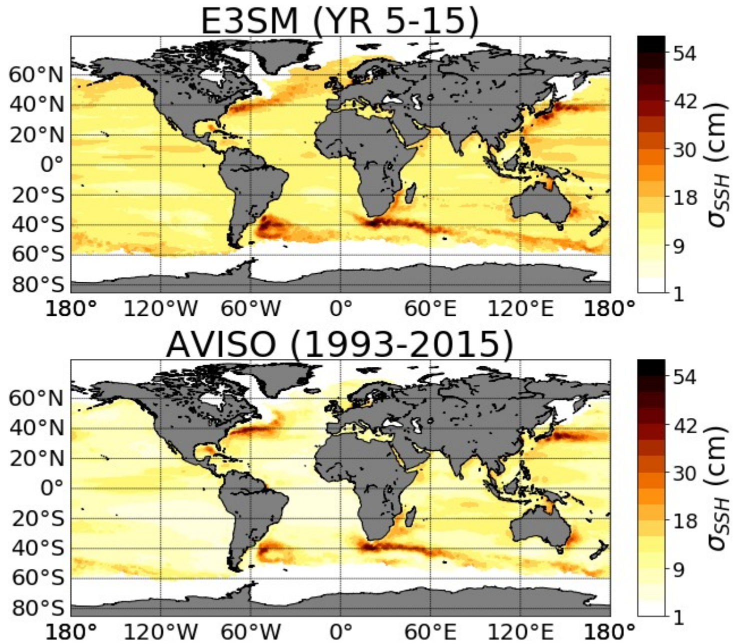

Figure 1. Sea-surface height variability measured as standard deviation from (a) E3SM high-resolution ocean-ice configuration and (b) AVISO observations.

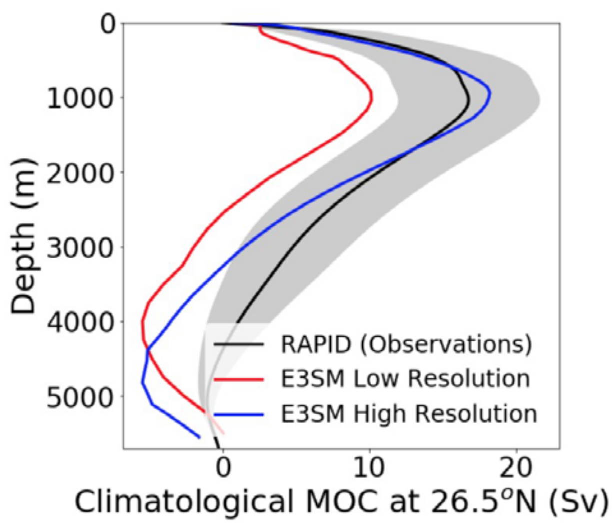

Figure 2. Climatological vertical profiles of the meridional overturning circulation (MOC) at 26.5^{o}N for low-resolution (red) and high-resolution (blue) configurations of E3SM v1. Also shown are observations from the RAPID mooring[1]. The gray shading shows one standard deviation about the observational average.

The impact of resolving the first Rossby radius of deformation on western boundary currents is shown in Figure 3. Here we show the time mean (10-year average) surface-current speeds simulated by our high-resolution and low-resolution E3SM configurations (both with identical forcing) alongside surface drifter observations (Laurindo et al. 2017) for the Gulf Stream region. Consistent with previous

[1] http://www.rapid.ac.uk/rapidmoc/

studies, the model representation of western boundary currents improves dramatically at high resolution. The magnitude and the width of the current is improved relative to observations. Further, the separation of the modeled western boundary currents is consistent with observations.

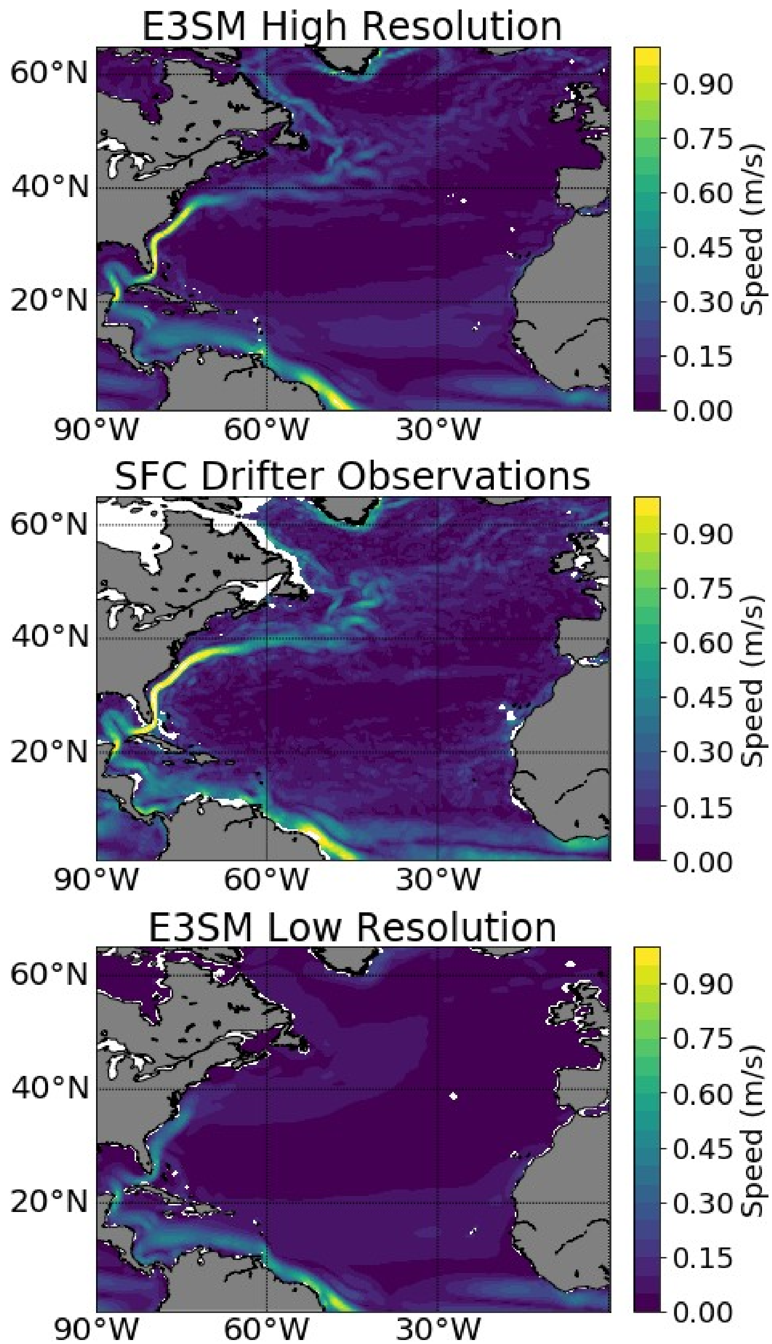

Figure 3. Surface-current speeds for the Gulf Stream. (a) E3SM high resolution, (b) Surface Drifter observations, and (c) E3SM low resolution (approximately one-degree). In all panels, surface current data sets are averaged over 10 years. The observational data set is described in Laurindo et al. (2017).

In Figure 4 we show the time mean (10-year average) surface-current speeds for the Southern Ocean. Again, E3SM high- and low-resolution configurations are compared to observations. In the low-resolution simulations, the Antarctic Circumpolar Current is very weak relative to observations. At high-resolution we find surface-current speeds that are consistent with observations. The E3SM mean eddy activity is also consistent with observations. Accurate representation of Southern Ocean eddy activity is critical, as Morrison et al. (2016) show that mesoscale eddies exert a large influence in the transport of heat in the Southern Ocean.

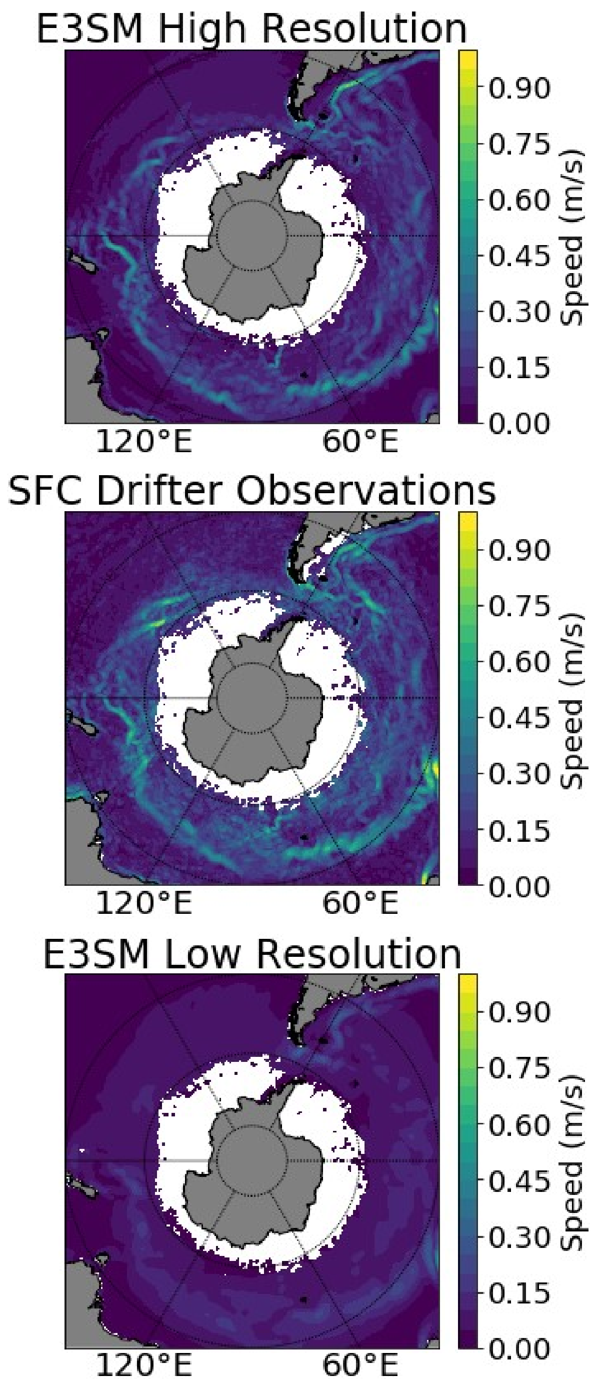

Figure 4. Surface-current speeds for the Southern Ocean. (a) E3SM high resolution, (b) Surface Drifter observations, and (c) E3SM low resolution (approximately one-degree). In all panels, surface current data sets are averaged over 10 years. The observational data set is described in Laurindo et al. (2017).

4.0 References

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