DOE/SC-CM-18-004

U.S. DEPARTMENT OF ENERGY | Office of Science

FY 2018 Fourth Quarter Performance Metric: Demonstrate ability to improve simulation of ocean sea-surface temperature using an eddy-resolving high-resolution E3SM-MPAS-Ocean configuration as compared to an eddy-parameterized low-resolution E3SM-MPAS-Ocean configuration.

September 2018

Contents

Figures

1.0 Product Definition

Sea-surface temperature (SST) plays a major role in the Earth's hydrologic cycle by affecting the exchange of water, heat, and momentum between the ocean, cryosphere, and atmosphere. As the climate warms, changes in SST will likely modify the location, frequency, and intensity of precipitation. In the ocean, it is expected that a high-resolution simulation (e.g., 10-km grid scale) will produce a more realistic evolution of SST due to inclusion of smaller flow scales and the need for fewer parameterizations of unresolved processes (such as mesoscale eddy effects). Previous studies (e,g,, Bryan et al. 2010, Small et al. 2014) have shown that the ability of an ocean model to realistically resolve mesoscale frontal structures in the SST can have a significant effect on, for example, global precipitation, suggesting that fine-resolution simulations may be necessary to produce high-fidelity climate projections. In this report, the improved realism of SST in high-resolution (HR) simulations compared to low resolution (LR) is investigated and confirmed using the DOE E3SM in fully coupled (ocean-atmosphere-cryosphere-land) mode.

2.0 Product Documentation

In order to investigate the effects of resolution on the SST, the low-resolution E3SM (of order 100 km for atmosphere/land and 60-30 km for ocean/ice) and high-resolution (of order 25 km for atmosphere/land and 18-6 km for ocean/ice) coupled simulations are analyzed and compared. The high-resolution E3SM Water Cycle experiment has currently completed 30 years, which will be compared with a companion low-resolution case of the same duration. Both simulations are time-slice experiments using perpetual 1950 greenhouse gas (GHG) and aerosol forcing. The ocean and sea ice states of both simulations were initialized from a short spin-up (3 years) of a CORE-II (observed-atmospheric; Large and Yeager, 2004) forced run. SST characteristics for the LR and HR ocean configurations are compared with historical climatological observations as well as satellite-derived products. Based on several metrics, the HR case is found to be more realistic than LR, although HR appears to significantly over-represent the SST variability in regions of strong eddy activity.

3.0 Supporting Materials

3.1 Instantaneous SST

Figure 1 shows snapshots of SST in the South Atlantic from the LR and HR simulations compared to the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) satellite-derived data product (http://marine.copernicus.eu). Visual inspection shows that the HR run is clearly more realistic based on the represented spatial scales and flow structures such as the Agulhas Current flowing around the tip of South Africa, and eddies spawned by dynamical instabilities. As noted above, resolving these smaller scales can result in much more realistic ocean-atmosphere interactions. However, does this mean that the SST is quantitatively "improved" in the HR relative to the LR when compared to observations?

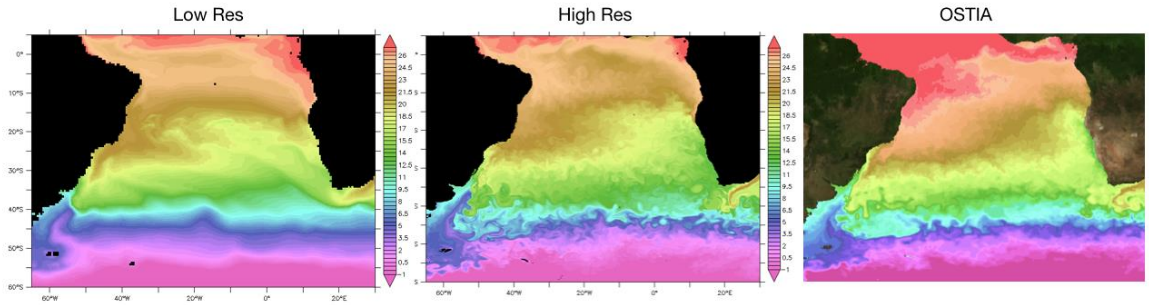

Figure 1. SST (ºC) on August 24 of year 20 from the LR (left) and HR (middle) simulations. SST from the 0.05x0.05º OSTIA satellite-derived product from August 24, 2018 is on the right.

3.2 Mean SST

Figure 2 shows a time series of the global mean SST for the duration of the simulations along with an estimate of the mean from the Hadley Centre monthly SST (observed) climatology from 1946-1955 (Rayner et al. 2003). The SST in both runs decreases over the first decade, with the LR case dropping by almost a full degree while the HR case changes by about 0.2º C. There are a number of possible reasons why the runs behave so differently, including changes in the resolution and tuning parameters of the atmosphere model, the use of the Gent-McWilliams (McWilliams and Gent, 1994) eddy advection parameterization in LR, or higher vertical resolution in the HR case (80 levels versus 60 in LR).

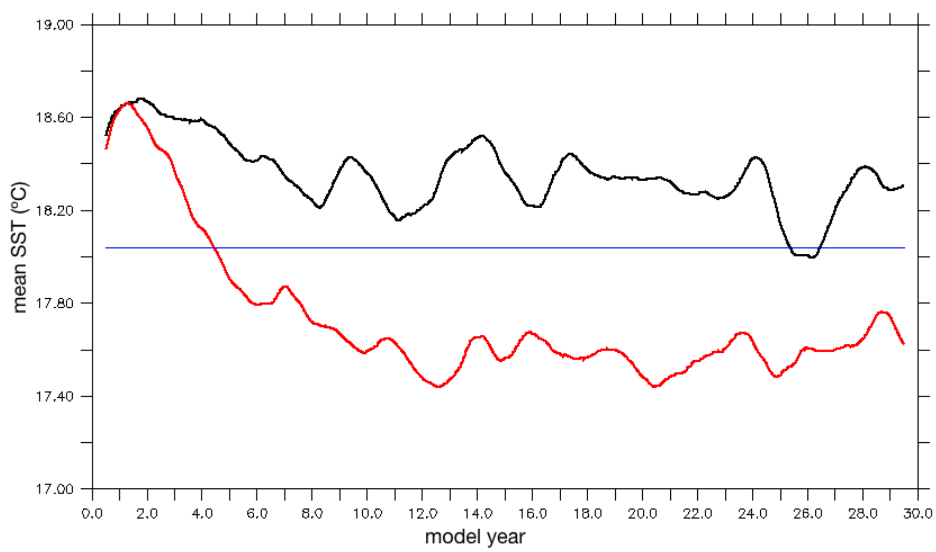

Figure 2. Globally averaged SST versus model year for HR (black) and LR (red) using a 12-month boxcar smoother. The blue line is the average over 1946-1955 from the Hadley Centre observed climatology.

Figure 3 shows the difference in time-mean SST with respect to the Hadley Climatology. The maps reflect the biases seen in the time series (Figure 2), with the LR case dominated by cold bias and the HR case by warm bias. The strong cold bias in the LR North Atlantic is related to the known problem of excessive sea ice in the Labrador Sea, which does not occur in the HR case. Note that the simulations share a warm bias in the eastern ocean basins due to a combination of relatively weak ocean upwelling and unrealistic stratus clouds. Statistically, the HR case has a lower absolute value for the mean bias (0.22 versus -0.54 for LR) and for the root-mean-square error (RMSE, 0.8 versus 1.4 for LR).

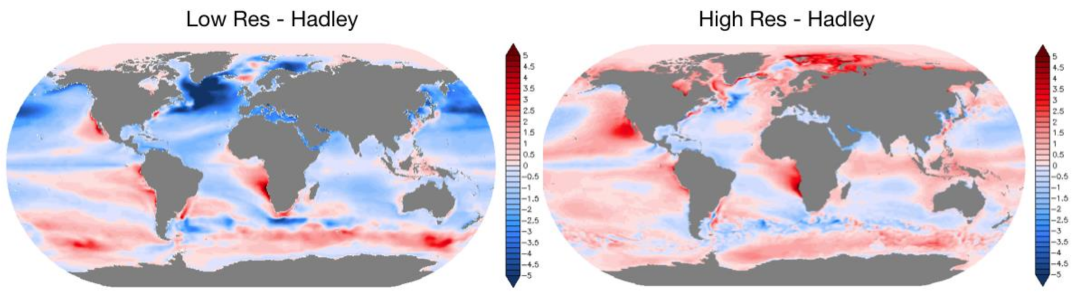

Figure 3. Difference between the time-mean (years 21-30) model SST and the Hadley SST climatology averaged over 1946-1955 (ºC).

3.3 SST Variability

Although the mean state is a very important diagnostic for model fidelity, improvements due to increased model resolution cannot be determined solely by mean biases and RMSE. We know that allowing spontaneous formation of turbulent mesoscale eddies results in increased realism of, for example, the sea surface height (SSH) variability and meridional overturning circulation (demonstrated in the Q1 metric and references therein https://climatemodeling.science.energy.gov/system/files/attachments/FY2018_First_Quarter_Metric.pdf). However, variability of SST may be even more directly important than SSH fluctuations to the climate system as a whole.

Figure 4 shows the standard deviation of SST derived from 5-day samples of the simulations and retrievals of SST from the Advanced Very High Resolution Radiometer (AVHRR) satellite data (https://lta.cr.usgs.gov/AVHRR) after the removal of the mean annual cycle. Even though the data is not from the 1950s, AVHRR is used for this comparison because the Hadley climatology is comprised of monthly observations, while AVHRR is available daily, and high frequency is necessary to resolve eddy effects (we assume that the characteristics of the SST variability during the late 20th century are not significantly different from mid-century). In general, the highest variability in the simulations occurs in regions of strong currents. This is expected for HR, but is somewhat surprising in the LR case since there are no explicit eddies, so it must be due to a different mechanism than that in an eddying ocean. The HR variability is clearly too strong when compared to AVHRR, but the location in eddy-active regions is quite realistic. Although not explicitly stated in the Q1 metric, the SSH variability in the HR model was also found to be significantly stronger in these regions than in altimeter data, so it is not surprising that the SST variability is also too large.

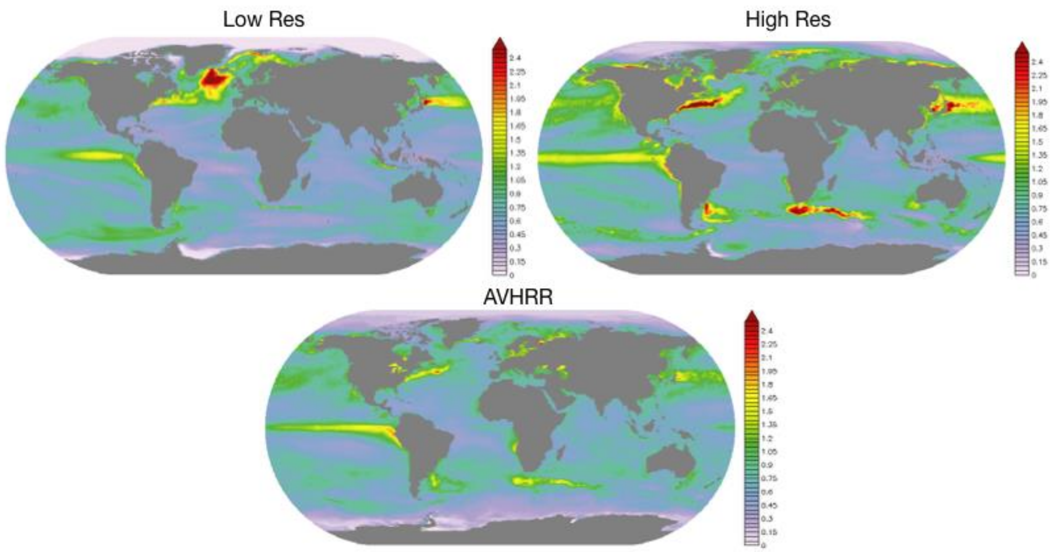

Figure 4. Standard deviation of SST (ºC) averaged over years 21-30 from the simulations and years 1994-2003 of AVHRR data, based on 5-day snapshots and with the mean annual cycle removed.

One useful way of comparing the statistics of models with data is via a Taylor diagram (Taylor 2001) since it can distill broad statistical characteristics of a simulation in a manner that can be quickly interpreted. Figure 5 compares the statistics of the standard deviation in simulated SSTs with AVHRR (i.e., the fields shown in Figure 4). While the correlation of the HR case with AVHRR is higher (0.78 compared to 0.51 for LR), the standard deviation of the LR case (0.28) is much closer to data (0.27) than the HR case (0.33) due to the excessive strength of HR variability noted above.

One measure of the fidelity of a model in a Taylor diagram is the RMSE, which is distance from the model point to the data point. In Figure 5, the distance from the LR and HR points to the AVHRR point is essentially identical; thus, using this metric, one cannot say one of the models is better. Note, however, that the variability in the HR case can likely be reduced by modifying model parameters, as discussed below. For example, if the standard deviation of the HR case can be decreased while maintaining the correlation (the red dot in Figure 5), it would clearly be an improvement compared to LR.

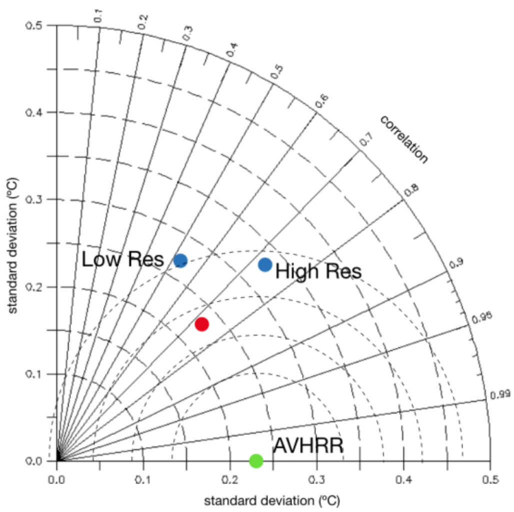

Figure 5. Taylor diagram of the SST standard deviation from the simulations (blue points) compared to AVHRR data (green point). The distance from the origin reflects the spatial standard deviation of the fields seen in Figure 4, and the angle represents the spatial correlation of each field with AVHRR (the data is perfectly correlated with itself). The distance from the model points to the AVHRR point (denoted by the dashed semicircles centered on the data) represents the root-mean-square error (RMSE) of the simulations with respect to the AVHRR data. The red circle denotes where the HR run wuld be located with reduced standard deviation while maintaining the same correlation.

As noted above, the correlation of SST variability in the LR case with data (Figure 4) is surprising since the model does not resolve mesoscale eddies at coarse resolution. As such, it is possible that the correlation coefficient in this case is artificially inflated due to processes unrelated to real-world variability. In the HR case, the regions of high variability are directly related to mesoscale eddy activity. This can be demonstrated by examining the covariance of SST and SSH since the latter is a direct measure of ocean internal variability, while the former can be affected by external forcing as well as internal dynamics. Figure 6 shows snapshots of SSH contoured over SST for the simulations and data, clearly showing qualitatively that they are closely related in strongly eddying regions. This is reflected quantitatively for the HR case by the covariance (Figure 7), which is quite high in the same regions as the SST variability (Figure 4). In contrast, the covariance is close to zero everywhere for the LR case, so there is essentially no dynamical relationship between variations in SST and SSH. This implies that the relatively high correlation of LR SST variability with AVHRR in regions of strong currents is not due to dynamics found in the real ocean, and is thus likely overestimated when used to assess model fidelity

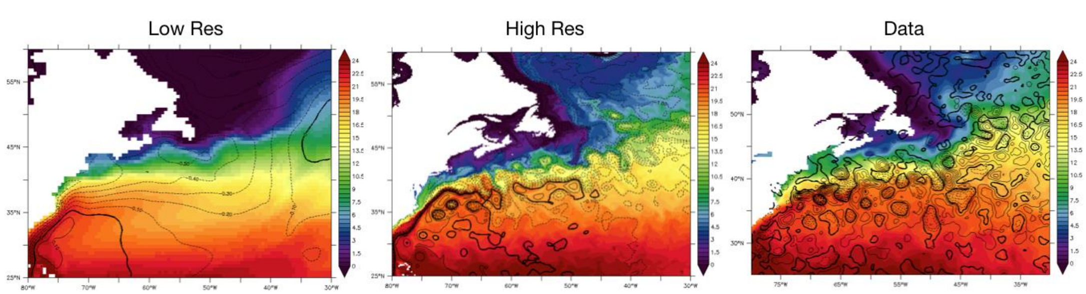

Figure 6. Snapshot of SST (ºC) and SSH (m) contours on Jan 1 of year 22 from LR (left) and HR (middle). The right panel shows SST from AVHRR and SSH from the Archiving, Validation, and Interpretation of Satellite Oceanographic (AVISO) altimeter-based product (https://www.aviso.altimetry.fr) from Jan 1 of the year 2000.

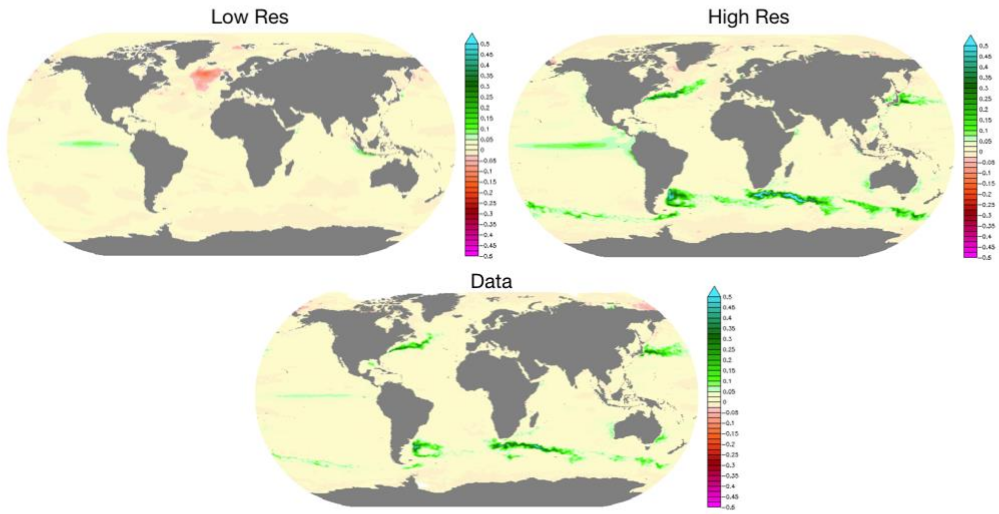

Figure 7. Correlation of SST and SSH variability from LR, HR, and data over the final 10 years of the simulations and years 1994-2003 of AVHRR and AVISO data.

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 Summary

Demonstrating that using a high-resolution (HR) ocean model results in an improved SST when compared with a low-resolution (LR) model is not straightforward without an in-depth analysis of the fully coupled system. That is, the possibility exists that the SST in the HR case appears to be much better than for the LR case, but could still result in an overall degraded climate simulation. With that caveat in mind, here we define “improved” as “bearing a closer resemblance to observations” and have provided several examples of the HR SST having higher fidelity than the LR case:

1. Snapshots of model SST are visually much more like observations in the HR case in terms of represented length scales (Figure 1).
2. Both the bias and RMSE of the time-mean SST are smaller for the HR case when compared to Hadley Centre data (Figure 3).
3. The correlation of the SST variability with AVHRR data is higher for the HR run (Figures 4 and 5).
4. The correlation of the SST variability with AVHRR in the LR case is likely an overestimate since the contributions from western boundary current regions are unrelated to the dynamics of these flows in the real ocean and in the HR case (Figures 6 and 7).

The only example where the HR SST clearly needs improvement is the high level of variability in eddy-active regions, where the standard deviation is often ~50% greater than calculated from AVHRR data. This behavior is a known characteristic of MPAS-Ocean that is also reflected by the root-mean-square SSH. It is unknown what effect this excessive eddy-related energy has on the climate system. In general, ocean modelers try to keep the system as under-damped as possible in order to allow a more freely evolving flow, and this is certainly the case here since the numerical scheme in MPAS-Ocean has relatively low intrinsic diffusion. Increasing the viscosity and/or tracer diffusivity in the HR setup would likely reduce the eddy variability to more realistic levels, though care must be taken that these changes do not degrade the simulation in other ways.

5.0 References

Bryan FO, R Tomas, JM Dennis, DB Chelton, NG Loeb, and JL McClean. 2010. “Frontal scale air-sea interaction in high-resolution coupled climate models.” *Journal of Climate* 23(23): 6277–6291, https://journals.ametsoc.org/doi/10.1175/2010JCLI3665.1

Hadley Rayner, NA. DE Parker, EB Horton, CK Folland, LV Alexander, DP Rowell, EC Kent, and A Kaplan. 2003, “Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century.” *Journal of Geophysical Research* 108(D14), https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2002JD002670

Large, WG, and SG Yeager. 2009. "The global climatology of an interannually varying air–sea flux data set." *Climate Dynamics* 33(2-3): 341–364, https://link.springer.com/article/10.1007/s00382-008-0441-3

McWilliams, JC, and PR Gent. 1994. “The wind-driven ocean circulation with an isopycnal-thickness mixing parameterization.” *Journal of Physical Oceanography* 24(1):46–65, https://journals.ametsoc.org/doi/abs/10.1175/1520-0485%281994%29024%3C0046%3ATWDOCW%3E2.0.CO%3B2

Small RJ, RA Tomas, and FO Bryan. 2014. “Storm track response to ocean fronts in a global high-resolution climate model.” *Climate Dynamics* 43(3–4):805–28, https://link.springer.com/article/10.1007/s00382-013-1980-9

Taylor, KE, "2001. Summarizing multiple aspects of model performance in a single diagram." *Journal of Geophysical Research* 106: 7183–7192, https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2000JD900719

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