Final Report for DE-FG02-05ER64119: Towards a High-Resolution Global Coupled Climate System for Prediction on Decadal/Centennial Scales.

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This grant period started just after the publication of Maltrud and McClean (2005). This paper described the first multi-decadal fully global ocean simulation configured at fine resolution (1/10-degree) such that mesoscale eddies were resolved in most of the global domain. Both a prototype fine-resolution fully coupled Earth System Model (ESM) simulation and a first-ever multi-decadal forced fine-resolution global coupled ocean/ice simulation followed as part of this grant. Science questions focused on the gains from the use of high horizontal resolution, particularly in the ocean and sea-ice, with respect to climatically important processes. Since our reporting period is over an extended number of years due to a renewal of the original grant and no-cost extensions, we will start this report by discussing the most recent results first and then review the earlier work.

The over-arching goal of this project was to contribute to the realization of a fully coupled fine resolution ESM simulation in which a weather-scale atmosphere is coupled to an ocean in which mesoscale eddies are largely resolved. The Community Climate System Model CCSM4, the antecedent to CESM, was used by the Center for Atmospheric Research to conduct standard resolution climate simulations for the Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5). A prototype version of CCSM4 was used to conduct a 20-year fine resolution fully coupled ESM simulation, the first of its kind, at Lawrence Livermore National Laboratory under the auspices of a LLNL Grand Challenge high performance computational award. Its components were the Community Atmospheric Model version 3.5 (CAM3.5), the Community Land Model version 3 (CLM3), the Parallel Ocean Program 2.0 (POP2), and the Community Ice Code version 4 (CICE4.0).

McClean, as part of this grant, contributed to all aspects of this simulation by working collaboratively with LLNL and National Center for Atmospheric Science (NCAR) scientists. She contributed to the experiment design, monitored the ocean and sea-ice as the simulation progressed, and analyzed ocean and sea-ice results upon its completion. She was the lead author of the first publication describing the model results (McClean et al. 2011). For the first time, realistic intense category 4 tropical cyclones were simulated in a fully coupled ESM. The cyclones caused cold water from below the surface mixed layer to move upward producing characteristic cold sea surface temperature (SST) wakes under and to the right of storm tracks. As well, the model correctly depicted the deepening of and warming below the ocean mixed layer that accompanies these storms.

Additionally, the model realistically reproduced the structure and pathways of explicitly resolved South Atlantic Agulhas oceanic eddies, the main constituent of the upper limb of the Atlantic meridional overturning circulation. These are absent in the oceans of standard climate models and are incorrectly represented in high-resolution ocean-only experiments forced with atmospheric fields derived from observations.

In parallel, stand-alone fine-resolution (1/10-degree) global ocean and coupled ocean/sea ice simulations forced with synoptic interannually-varying reanalysis atmospheric fluxes were conducted as part of this grant. The component models used in these simulations were POP and CICE; the coupled POP/CICE simulation was run in the CESM framework with Coordinated Ocean-Ice Reference Experiment 2 (CORE2) interannually varying forcing (IAF) as the data atmosphere component. This forcing consists of the NCEP atmospheric state for near surface vector winds, air temperature, specific humidity and density, and satellite-based observations of radiation, sea surface temperature (SST), sea-ice concentration, and precipitation (Large and Yeager, 2009). These forced simulations were needed to understand ocean/sea ice processes in this fine resolution regime without the complications of an active atmosphere, and to better understand the cause of biases when active components are coupled together. As a result of forcing with observed atmospheric conditions over the latter part of the 20th Century and the start of the 21st Century these simulations provide depictions of sea-ice and ocean conditions for those years. They can be compared with historical observations to establish model veracity, and can then be used to explain ocean and sea-ice processes that cannot be determined from the observations alone. For example, variability in ice cover in marginal ice zones can be related to atmospheric and oceanic variability; the latter will be more realistic since ocean current cores are now adequately resolved. A measure of the robustness of the model physics and dynamics once transitioned into the high-resolution regime can also be obtained from these runs.

One specific computational goal of the project was the completion of the forced fine-resolution multi-decadal global POP/CICE simulation. This 40-year simulation was run on the IBM iDataPlex cluster computer known as Yellowstone at the NCAR-Wyoming Supercomputing Centre. Climate Simulation Laboratory (CSL) computer resources were obtained for the simulation through NCAR's competitive award process; the simulation was completed in the summer of 2013. To produce this realistic multi-decadal global fine-resolution coupled ocean and sea ice simulation, simulations were performed both at high resolution (1/10-degree) and at a lower resolution (1-degree) to test sensitivity to parameter choices and atmospheric forcing. The lower resolution configuration allowed for fast turnaround and was used to test sensitivities to ice parameter choices that were not particularly sensitive to horizontal resolution. One challenge that arose was the occurrence of ocean-ice instabilities over shallow topography when the sea-ice and ocean components were run together at high resolution. The use of an equivalent stand-alone POP simulation allowed us to identify the cause of the instability and correct it. Results of this work have been presented incrementally at CESM workshops. Comparisons of sea ice concentration, extent, thickness distribution, and speed with observations in the Arctic and Subpolar North Atlantic indicate that it is a realistic simulation. A manuscript describing the 0.1-degree POP/CICE set-up and the accompanying sensitivity simulations will be completed and submitted for publication shortly.

The analysis of this forced global 0.1-degree POP/CICE simulation in the Bering Sea was the subject of an SIO Ph.D. dissertation successfully defended by Linghan Li (SIO) in September 2013. Li examined the mechanisms responsible for seasonal variability and extreme events occurring in Bering Sea ice cover during 1980-1989. Particularly she evaluated how winds, surface heat fluxes, and oceanic currents contributed to thermodynamic and dynamic volume sea ice tendencies. This period was chosen as a benchmark of seasonal variability in the Bering Sea as it pre-dates the rapid acceleration of summer sea ice loss observed in the Arctic in the 1990s and 2000s. McClean was on her thesis committee and two papers are being prepared for publication from this work.

All these simulations were built on the foundation of earlier testing and simulation at lower resolution or in less sophisticated coupling frameworks that were conducted earlier in the grant. Many of the publications arising from these earlier studies were by postdoctoral researchers and students working with McClean, who co-authored all of their publications. Asterisks indicate a student or post-doctoral researcher.

Global coupled POP/CICE was run in an eddy-permitting configuration (0.4-degree) whereby the ocean and ice were coupled through a driver that also read the atmospheric forcing. In this case, the interannually varying atmospheric forcing (NCEP/NCAR) was interpolated onto the model's computation grid prior to the model run unlike the CESM coupler that interpolates the forcing during the run. Two papers resulted from these simulations: Prasad* et al. (2005) and Ivanova* et al. (2012). In the former study, the mechanisms responsible for the initiation, maintenance, and termination of the western Cosmonaut polynya were investigated. Polynyas are important to the polar surface atmospheric heat budget, as these areas of open water within the ice pack are often the location of exchange of heat and moisture from the ocean to the atmosphere. These features are not resolved in standard resolution climate models. In Ivanova* et al. (2012) the simulated sea-ice fields were compared extensively with observations in the Arctic and Greenland-Iceland-Norwegian (GIN) Seas. They computed upper ocean mixed layer heat budgets in the marginal ice zone in the GIN seas both seasonally and for different phases of the North Atlantic Oscillation in the 1990s. Particularly, the relative roles of net surface heat flux and ocean advection in the marginal ice zones were evaluated in a model where ocean flows were better resolved than in standard resolution models.

A major science goal of this project was to understand how the explicit resolution of ocean mesoscale eddies, the realistic resolution of narrow mean ocean currents, and eddy-mean flow interactions, change the depiction of processes that are important to climate in the high-resolution regime. This theme resonated throughout the whole period of the grant and a number of climate processes were considered using a variety of approaches. Note that mesoscale eddies are resolved up to sub-polar latitudes by our nominal 1/10-degree global grids; at increasingly higher latitudes an increasing fraction of the smallest wavenumbers is not resolved.

It was first necessary to understand how well high resolution POP statistically depicted the mean and variability of the general circulation of the ocean. Ocean observations of sufficient temporal and spatial resolution to allow near-global evaluations were limited to the upper ocean. In particular, sea surface height anomalies derived from altimetry and velocities at 15m from drifting buoys were available for multiple decades. Measures of transports through choke points such as the Indonesian Throughflow and the Drake Passage provide another important check of model performance. McClean et al. (2006; 2008) compared statistics of fine resolution POP output and these observations, as well as time series such as mixed layer depth and flow variability at point locations. Both the mean and the variability of the upper ocean as represented by simulated ocean currents and sea surface height variability showed very good agreement with the measures from altimetry and surface drifting buoys. Lenn* et al. (2011) compared eddy momentum fluxes from POP and observations collected in a repeat section across the Drake Passage. The measurements themselves were novel and the good agreement between the model and data encouraged us that the model was satisfactorily capturing the dynamics and variability of the ACC during the analysis period.

Griesel* et al. (2009; 2010) used Lagrangian particles that were deployed and advected online through the three-dimensional velocity field of POP to understand mesoscale stirring and advection in the Southern Ocean. Mixing in the Southern Ocean impacts the overturning circulation of the SO and hence the entire global overturning circulation. Griesel et al (2009) discusses the challenges of interpreting diffusivities calculated from eddy heat fluxes in eddying models due to their strong horizontal rotational component. Griesel et al. (2010) examined the spatial distribution of Lagrangian subsurface isopycnal eddy diffusivities in the Southern Ocean, as depicted by POP, and found that the diffusivities were horizontally highly variable with no latitude dependence. Rainville* et al. (2007) examined the formation and variability of North Pacific Subtropical Mode Water (STMW) in the Kuroshio Extension of the North Pacific as depicted by high-resolution POP; mode waters formed due to convection in winter are capped off during summer and re-emerge in subsequent winters to impact SST. They found that the distribution of STMW was highly variable in space and time and was highly dependent on eddies and where it was renewed during the previous winter. Both advection and mixing played important roles in removing STMW from the formation region. Wolfe* et al. (2008) examined vertical heat transport and vertical turbulent diffusivities in POP and the MITgcm. They arrived at the important conclusion that the Munk and Wunsch (1998) estimate of the energy needed to close the meridional overturning circulation is an overestimate due to the neglect of mesoscale eddies. Most recently, Wang* et al. (2013) reconstructed the ocean interior from surface field of a 1/10-degree North Atlantic simulation run by McClean as part of an earlier DOE/Climate Change Prediction Program (CCPP) grant. The method was most successful in the energetic Gulf Stream region indicating that high resolution POP was a useful test-bed for the development of this method for use in the real ocean using surface observations. Finally, Bryan et al. (2010) was a study of mesoscale air-sea interaction in the frontal zones of western boundary currents. The study used three coupled models, including the LLNL ESM, where eddies were either parameterized or explicitly resolved in the ocean component. The importance of this paper is that it showed the air-sea interaction in western boundary current frontal zones is only realistic captured when oceanic mesoscale eddies are explicitly resolved.

Overall, it was found that the mean and variability of the circulation of eddying ocean simulations were in keeping with real ocean observations; the observations are predominantly of the upper ocean. The presence of eddies was found to be important in the spatial distribution of the formation of mode waters, which are responsible for the uptake of heat into the ocean. Eddy-driven mixing and advection are of leading order importance in the Southern Ocean, where eddy processes account for both the zonal and vertical transfer of tracers across the Antarctic Circumpolar Current (ACC). POP provided a depiction of the spatial variability of eddying mixing in the Southern Ocean. From vertical turbulent diffusivities in eddying POP the importance of eddies in closing the energy budget of the meridional overturning circulation was identified.

Over the lifetime of the grant McClean collaborated with Maltrud and Hunke who are developers of POP and CICE, respectively, at Los Alamos National Laboratory. She involved them in the student/postdoc studies so that mentorees could benefit from a direct connection with the model developers. McClean was also a co-author of a study using high-resolution POP to study El Niño effects off South Australia (Middleton et al., 2007). Also she co-authored Piacsek et al. (2008), in which the characteristics of GIN Sea water masses were compared with those simulated in her earlier global eddy-permitting POP simulation that was forced with interannually varying atmospheric fluxes. The GIN Sea is the site of convection zones where North Atlantic Deep Water forms and sinks to become the southward arm of the Atlantic meridional overturning circulation. Hence the realistic depiction of these water masses is climatically important.

Finally, with respect to broader impacts, McClean and Elena Yulaeva who works as a programmer/analyst for McClean participated in a high school teacher's workshop held at SIO in winter of 2012. McClean gave a lecture on climate and high-resolution modeling to the teachers, particularly sharing visualizations of high-resolution ocean and atmospheric simulations. Yuleava demonstrated software that could be used in classrooms to explain climate modeling to high school students.

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