FY 2021 First Quarter Performance Metric: Demonstrate Advanced Capabilities for Representing Waves within Earth System Models, a Key Process in Coastal Storm Surge Impacts

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1.0 Product Definition

Wind-generated waves are involved in several important processes in the global climate system. This includes the mediation of momentum, heat, and mass fluxes between the ocean and atmosphere (Cavaleri et al. 2012). Waves also play an important role in the cryosphere, where there are feedbacks between wave dissipation and sea ice fracture in the marginal ice zone (Squire et al. 1995). Of particular interest to U.S. Department of Energy (DOE) mission questions is the response of the water surface level to shoaling and breaking waves in coastal regions. This additional “wave setup” (Longuet-Higgins and Stewart 1964) can represent a large portion of the overall mean water surface elevation in tropical cyclone flooding events, with implications to energy infrastructure in coastal regions. The wave setup process is illustrated in Figure 1(a).

Wind waves occupy a portion of the energy/frequency spectrum that is distinct from the longer-period ocean waves (tides, storm surges, tsunamis, etc.), which are resolved in some ocean circulation models (Wright et al. 1999). Since wind waves have periods on the order of 1-10 seconds and wavelengths on the order of 10-100m, their time and length scales are too fine to be resolved explicitly over the entire globe. Therefore, “phase-averaged” wave models are typically employed in large-scale applications (Cavaleri et al. 2007). These models describe the evolution of wave action (which is closely related to wave energy) as it propagates in latitude, longitude, frequency, and directional space (Tolman 1991). The frequency/direction spectrum can then be used to calculate several statistical quantities describing the wave field such as significant wave height, mean direction, and mean period. Another important quantity is the Stokes drift, shown in Figure 1 (b), which is the mean velocity induced by wave motion in the propagation direction.

![Figure 1](image.png)

**Figure 1.** Examples of relevant wave processes. (a) Wave setup contribution to extreme water levels. (b) Stokes drift velocity due to asymmetric crest and trough particle velocities.

Since phase-averaged wave models resolve a frequency/direction spectrum at each model grid point in the ocean, the number of model unknowns is high. This large number of unknowns, combined with the complexity of wave physics parameterizations, which describe generation, dissipation, non-linear interactions, etc., makes these wave models very expensive additions to Earth system models. Therefore, our goal is to use unstructured meshes in order to economically resolve wave processes globally across the open ocean and coastal regions of interest. Using these meshes, the computational expense associated with the high mesh resolution required for coastal regions can be balanced with
efficient use of coarse resolution for open ocean basins. As will be shown in the results section, coarse unstructured meshes with coastal refinement can provide comparable accuracy to global high-resolution structured meshes. Unstructured meshes can achieve this level of accuracy at significantly reduced computational cost. This allows for an unprecedented capability to efficiently include wave processes at both global and coastal scales in Earth system models.

2.0 Product Documentation

The most recent version (6.07) of the National Oceanic and Atmospheric Administration (NOAA) WAVEWATCHIII® model has been integrated into the DOE Energy Exascale Earth System Model (E3SM) as the wave model component. Initially, the model used the traditional structured mesh configuration. However, in order to enable global-to-coastal wave modeling for E3SM, modifications were made to extend WAVEWATCHIII® to global, unstructured mesh domains. Previously, unstructured meshes had been used successfully in hurricane wave prediction studies but were limited to regional domains (Abdolali et al. 2020). Here, we implement and validate, for the first time, the performance of unstructured meshes for global domains with coastal refinements, which are appropriate for climate modeling applications within E3SM.

The triangular unstructured mesh considered in this study was generated using open-source mesh generation software (Roberts et al. 2019) and was designed to align with early versions of meshes under consideration for version two of E3SM (Hoch et al. 2020). The mesh has 2-degree resolution globally and transitions to ½-degree resolution in regions shallower than 4km. The 4km threshold was chosen to resolve coastal areas between the continental shelf break and the shoreline. A 10% element grade is enforced between the ½- and 2-degree resolution. The resolutions chosen allows the unstructured mesh to be readily compared against structured meshes with global uniform resolutions of ½ degree and 2 degrees. An image of the mesh is shown in Figure 2.

This global unstructured mesh capability has been validated against wave buoy measurements in order to assess overall suitability for use in E3SM, in terms of both accuracy and efficiency. We have compared modeled wave results for June-October 2005 with observations from the National Data Buoy Center (NDBC; Meindl and Hamilton 1992) along the U.S. coast. Additionally, the comparisons between the ½-degree and 2-degree structured meshes provide a sense of how well the unstructured mesh balances the accuracy and efficiency of the two different resolutions. The model was forced using atmospheric data from the Climate Forecast System Reanalysis (CFSR; Saha et al. 2010) product and was not coupled to other Earth system model components for this study.
3.0 Results

The goal of this validation study is to demonstrate that an unstructured mesh can provide increased efficiency over global high-resolution structured meshes without significantly degrading their accuracy in coastal areas. As will be demonstrated below, our results show that in the 2-degree regions of the unstructured mesh, the accuracy is similar to that of the 2-degree structured mesh. This level of resolution provides relatively good agreement with the ½-degree structured mesh in open ocean basins. However, in the ½-degree regions of the unstructured mesh, the solution greatly improves upon the 2-degree mesh and is of similar accuracy to the ½-degree structured mesh. This balance of high to low resolution allows for a large improvement in computational expense.

A comparison of the computed significant wave height solution against the buoy observations is shown in Figure 3 and Figure 4, for the U.S. east and west coasts, respectively. The RMSE plots in subplot (a) of these figures demonstrate that the ½-degree structured mesh is consistently in better agreement with observations than the 2-degree mesh, especially for shallower stations. At many shallow stations, the accuracy of the unstructured mesh is in good agreement with the ½-degree structured mesh due to its ½-degree refinement region. In shallow regions, the 2-degree resolution leads to inaccuracies that are improved upon by the unstructured mesh. Subplots (c) and (d) show the binned, normalized distributions of bias and relative errors, respectively. These distributions show all modeled and observed error values over the simulation period. More peaked distributions in (d) relative to (c) indicate largest errors occur during extreme wave heights.
Figure 3. Comparison between modeled results and NDBC buoy data for the 2-degree structured, unstructured, and ½-degree structured meshes in the mid-Atlantic east coast region. (a) Root mean squared errors (dots) for each mesh resolution along with station depth (grey line). (b) Geographic location of each station. (c) Normalized distribution of bias errors between the model and observations over the simulated time period. (d) Normalized distribution of relative errors.

Figure 4. Same as Figure 3 for stations on the west coast.
Figure 5 shows the average and maximum relative differences for the 2-degree structured and unstructured meshes compared to the ½-degree structured mesh. Overall, the open ocean differences between 2-degree resolution (for both structured and unstructured meshes) and the ½-degree structured mesh are less than 5% in the Southern Ocean and even lower in equatorial regions. This indicates that the coarser-mesh resolution does not greatly degrade solution accuracy in these areas. Additionally, the unstructured mesh performs similarly to the 2-degree mesh in the deep ocean. For the refined U.S. coastal regions in the unstructured mesh, the solution accuracy is very close to that of the ½-degree mesh. The unstructured mesh far out-performs the 2-degree structured mesh in these regions.

**Figure 5.** Mean (left panel) and maximum (right panel) absolute relative differences in significant wave height between the unstructured and ½-degree structured meshes (top row) and the 2 degree and ½ degree structured meshes (bottom row).

Figures 3-5 establish that the unstructured mesh provides accuracy on par with that of the ½-degree structured mesh in the high-resolution region. However, since the unstructured mesh uses 2-degree resolution over most of the globe, it is expected to be significantly more efficient. This is demonstrated in Figure 6. This figure shows the strong scaling results for each of the three meshes using between 36-1800 processors. The unstructured mesh provides between a 2-10 times speedup over the ½-degree structured mesh depending on the number of processors considered. Although the ½-degree structured mesh scales better than the unstructured mesh due to the larger number of grid cells, it reaches a communication bottleneck before it is able to reach a faster wall clock time than the unstructured mesh. The peak throughput of the unstructured mesh is 10.9 simulated years per day, nearly matching the 2-degree structured mesh, which achieves 12.1 simulated years per day.
In summary, the global unstructured mesh capability developed for WAVEWATCHIII® within E3SM nearly matches the accuracy of high-resolution structured meshes in refined regions. Due to the coarse resolution of the unstructured mesh in the deep ocean, it runs more efficiently than global structured meshes with uniform high resolution, without sacrificing accuracy. This capability positions E3SM to be the first Earth system model to include coupled feedbacks among waves, atmosphere, ocean, and sea-ice across global and coastal scales. For further details, see the paper currently under review: Brus et al. 2020.

### 4.0 References


