3D IPE to WAM Regridding Benchmark

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Background

The NOAA Space Weather Prediction Center (SWPC) is interested in coupling the Ionosphere Plasmasphere Electrodynamics (IPE) model with the Whole Atmosphere Model (WAM). Part of the functionality required by the coupling is to regrid a 3D IPE grid with vertical dimension defined in height to a 3D WAM grid with vertical dimension defined in pressure. One complication for this application is that the vertical fields of the WAM grid are changing dynamically during the simulation. The Earth System Modeling Framework (ESMF) team agreed to benchmark the grid remapping required for coupling these models, and this report presents initial results.

ESMF performs regridding in two steps. It first calculates the interpolation weights from the source grid to the destination grid using a function called ESMF_FieldRegridStore(), and then applies the weights using a function called ESMF_FieldRegrid().

In this analysis, we focus on ESMF_FieldRegridStore(). Interpolation weights were generated for the transformation from the 3D IPE grid to the 3D WAM grid, and performance measured for a range of processor counts (1-512). Using the full 3D capability for every time step represents an upper bound to the time required for the calculation. However, the grids only change every time step in the vertical dimension. In the next phase, we plan to use this fact to optimize the generation of weights by only re-computing the vertical part of the remapping every time step. If the WAM grid is distributed in the horizontal plane only, the 1D vertical interpolation can be done quickly on each processor without any communication overhead. This next phase is expected to improve performance, and will be described in an update to this report.

In addition to examining the performance of grid remapping for a 3D case, in this report we also look at the quality of the generated weights.

The benchmark was performed on the Yellowstone HPC system at NCAR. Yellowstone is based on IBM's iDataPlex architecture with Intel Bridge processors. We performed the scalability test using 1 to 512 processors. The ESMF version used in this test is ESMF_6_2_0_beta_snapshot_15.

The goal in this initial report was to measure the timing and accuracy of the 3D regridding. Therefore, instead of developing a custom application we chose to use an existing ESMF application that would let us achieve both of these goals as quickly as possible. The ESMF_RegridWeightGen application takes in two grid files and generates a file of regrid weights. This application uses all of the code that ESMF uses in regridding so it makes a

convenient platform for testing the timing and accuracy of ESMF regridding. In this report we use a slightly modified version of this program with timing routines added.

A difference between this benchmark and the actual application is the parallel distribution of the grids. ESMF_RegridWeightGen distributes the grids across the processors evenly, based on the description in the grid file. That means that for the benchmark, each grid is decomposed by splitting it first across vertical layers. In the actual application, the IPE grid is split up in a block decomposition manner based on flux tubes. All the nodes in one flux tube are in the same processor. The WAM grid is decomposed along the latitudes, but in order to get better load balance, the rows are shuffled so that the grid points are evenly distributed over all the processors. During ESMF interpolation weight calculation the grids are internally redistributed in order to put the pieces of the grid with the same physical location onto the same processor. Because of this, we expect the weights in the benchmark and the actual application to have the same accuracy. We expect a minimal effect on the timing.

In order to use ESMF_RegridWeightGen it was necessary to generate grid files corresponding to the IPE and WAM Grids.The 3D IPE grid was constructed using the data provided by Naomi Maruyama of NOAA SWPC and the 3D WAM grid was constructed based on the information provided by Jun Wang of NOAA EMC and Rashid Akmaev of NOAA SWPC. The 3D WAM grid used in the benchmark has fixed height at each vertical layer that is an approximation of the real WAM grid. Externally the IPE and WAM grids are stored in NetCDF files using the UGRID format, a proposed CF convention unstructured grid data model (https://publicwiki.deltares.nl/display/NETCDF/Deltares+CF+proposal+for+Unstructured+Grid+data+model). After being read in, the IPE and WAM grids are represented internally as ESMF 3D unstructured Mesh objects.

The details of the IPE grid and the WAM grid are described in the following sections.

Ionosphere Pasmasphere Electrodynamics (IPE) Grid

An IPE grid is defined as a set of flux tubes. There are 80x170 flux tubes in each hemisphere. Each flux tube has different number of grid points from 90km altitude at the lowest point up to 360,000km at the highest. Figure 1 shows the flux tubes along one meridian. The tubes are clipped to 782km in height.

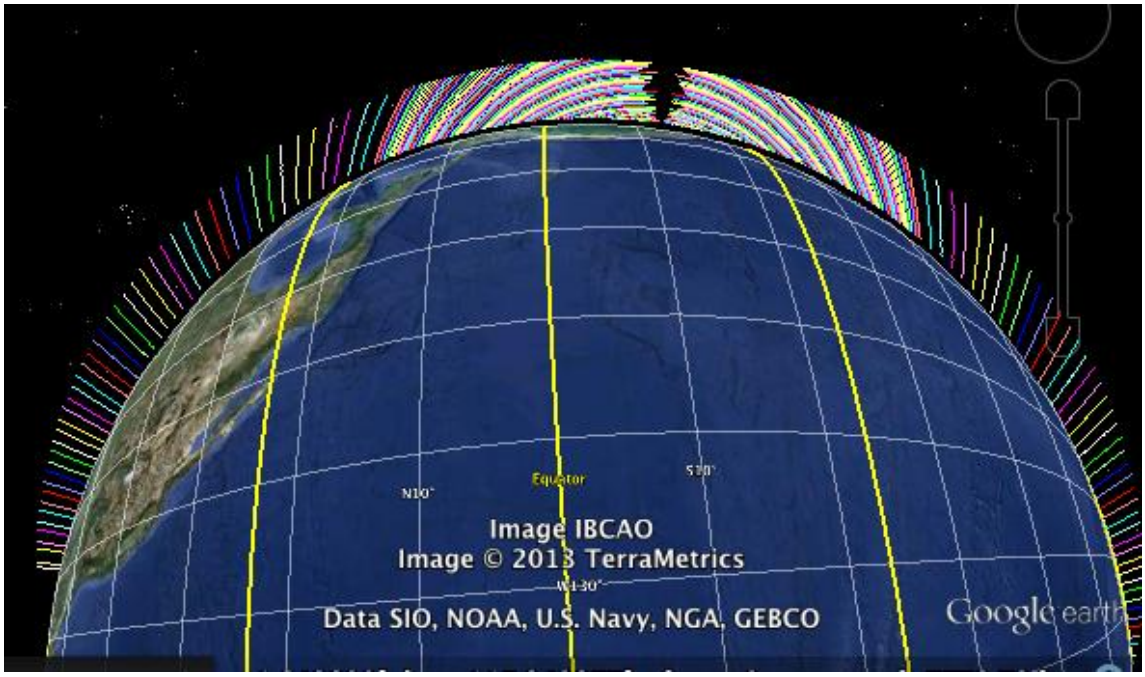

Figure 1 Flux tubes along one meridian in the IPE grid.

To construct an ESMF mesh from this grid, we first constructed 2D meshes using all the grid points at the same height from all the flux tubes. The total number of grid points on the lowest height, 90km, of the IPE grid is 80x170x2=27,200 for the entire hemisphere. At higher altitudes, there are fewer grid points because not all the flux tubes reach to the same height. Figure 2 shows a 2D IPE grid at the 90km height. Note the geomagnetic equator is not aligned with the geographic equator; it is in a sinusoidal shape as seen in Figure 2 where there is a gap separating the North and South Hemispheres. The equatorial gap is about 4 degree in latitude, which is the nature of the IPE grid because the flux tubes become horizontal at the magnetic equator. Also note that the grid cells are much denser around the equatorial area than the ones at the higher latitude. Figure 3 shows another 2D IPE grid at the altitude of 782km. You can see that there are much fewer grid points around the geomagnetic equatorial area.

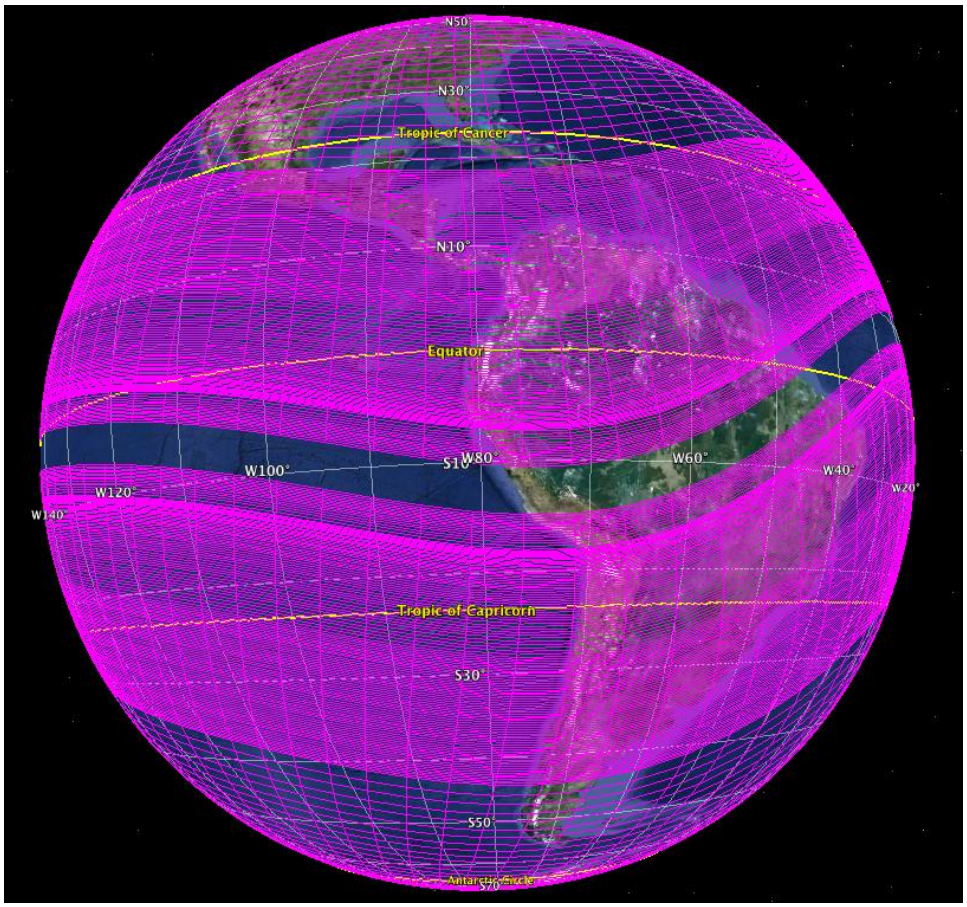

Figure 2 A 2D IPE grid at the altitude of 90km.

A 3D IPE grid is represented as an ESMF_Mesh object. We connected the neighboring quadrilaterals at consecutive levels into hexahedrons. When there are fewer grid points along one meridian at the upper level, we constructed prism cells (where the bottom is a quad and the top is a line) at fixed intervals to compensate for the difference. Figure 4 shows all the prism cells in the 3D IPE grid. The pink lines are the bottom quads and the yellow lines are the top lines of the prisms. The short white lines are the triangle faces on the two sides of the prisms. We constructed the 3D grid using the grid points up to 620km height because that is the area that overlays with the WAM grid. The 3D grid has a total of 77 levels and 1,684,480 grid points. The total number of cells is 1,655,680.

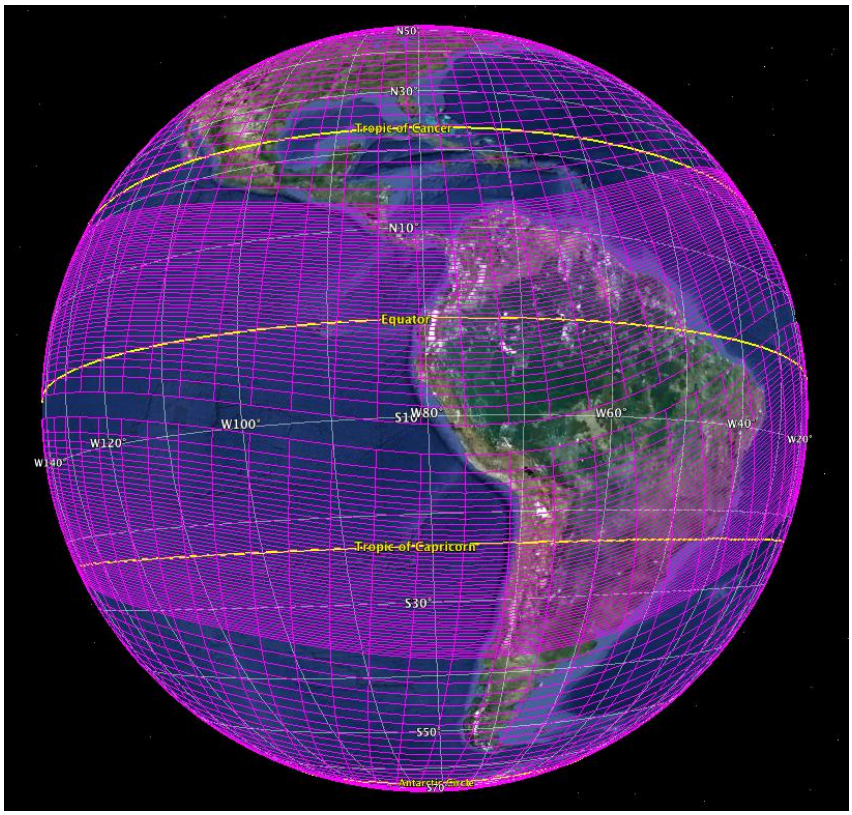

Figure 3 A 2D IPE grid at the 782km height.

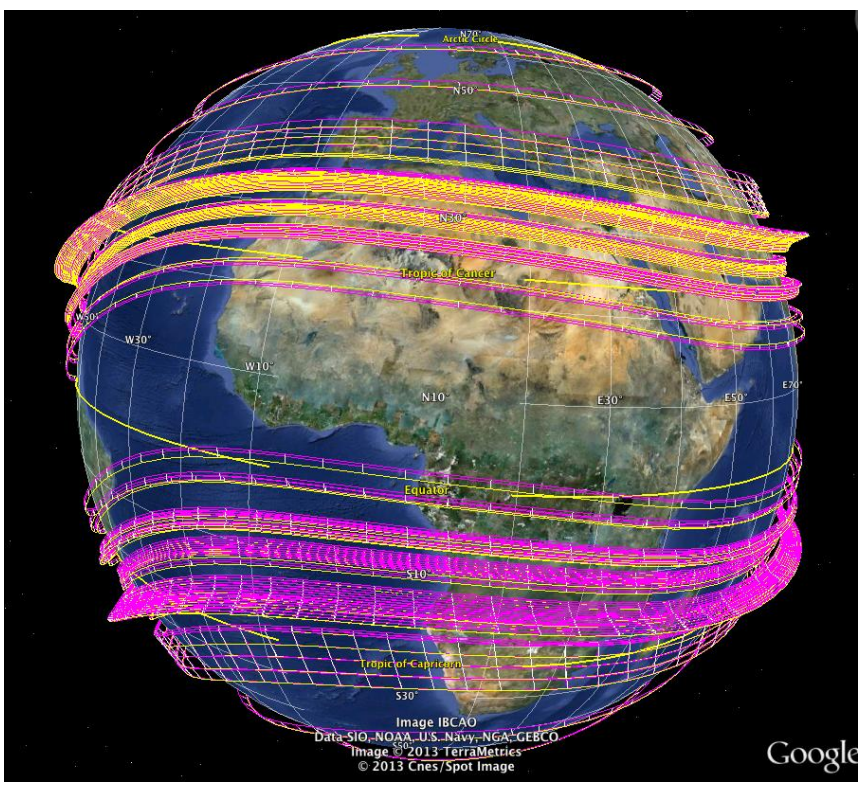

Figure 4 The "prism rings" in the 3D IPE Grid

3D WAM Grid

The Whole Atmosphere Model (WAM) is a 150-layer general circulation model based on the U.S. National Weather Service's operational Global Forecast System (GFS) model extended to cover the atmosphere from the ground to about 600km.

The WAM model runs at a spectral resolution T62 (roughly 1.8^o x 1.8^o resolution). The WAM grid at each horizontal layer is a reduced Gaussian grid with 94 grid points in latitude and a maximal 192 grid points in longitude. The number of grid points at each latitude has a Gaussian distribution with the most points in the equatorial area. The vertical layers are in the pressure field. The top pressure level is near a nominal altitude of about 600km. The pressure values at each grid points are different and it changes at every time step as well. In order to regrid the IPE grid to the WAM grid, we have to convert the pressure field to the height field. Currently, we built a 3D WAM grid using the global mean mid-level height values for medium-level solar activities provided by Rashid Akmaev of the SWPC. Thus, each of the 150 vertical layers has a fixed height value. The highest level in this sample data set is 591.44km. In the future it may be expanded to 700-800km.

To construct a 3D WAM grid, we first constructed a 2D mesh for each vertical layer. Since the number of grid points at each latitude is different, we represented the 2D mesh as a combination of quadrilaterals and triangles (Figure 5). The 2D meshes at all the vertical layers are the same. Therefore, we simply connected the quads or triangles between two adjacent layers into hexahedrons or prisms to form the 3D WAM grid. Since the IPE grid starts from the height of 90km, we thus cropped the vertical layers below 89km. The resulting 3D WAM grid has 55 vertical layers with heights from 89.74km to 591.44km. The total number of grid points in the WAM grid is 718,960 and the total number of cells is 713,124.

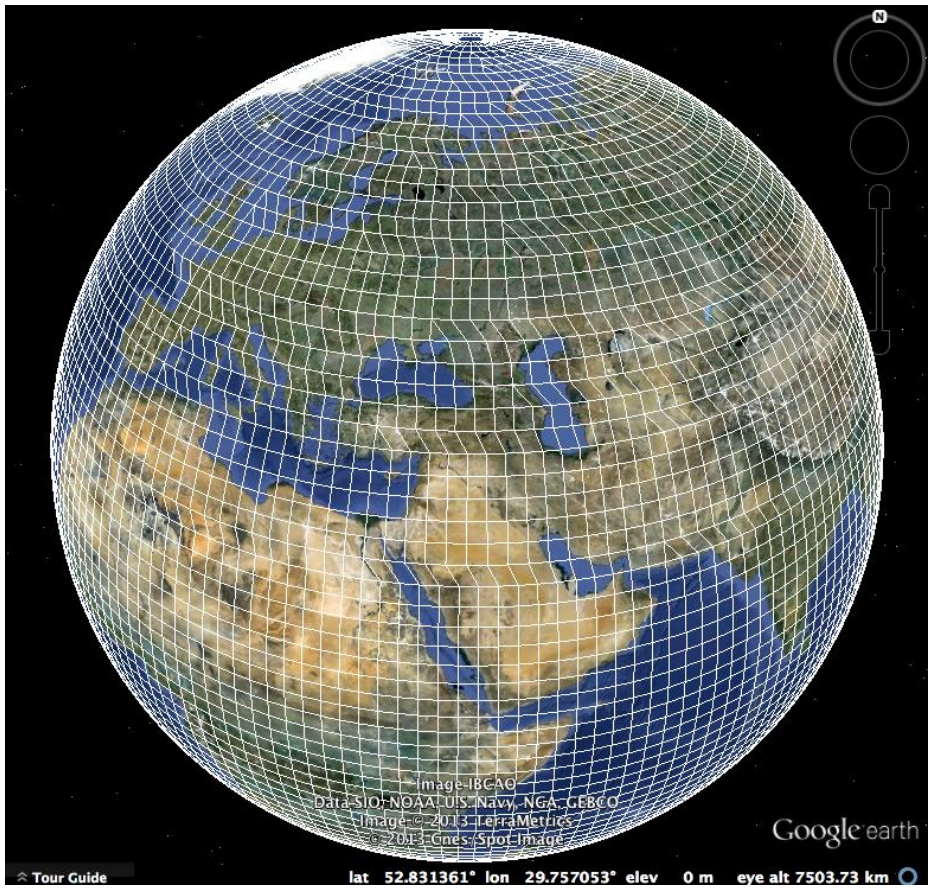

Figure 5 A 2D WAM grid represented with quadrilaterals and triangles.

Results

Weight Quality

We performed bilinear regridding from the IPE grid to the WAM grid and vice versa using the ESMF_RegridWeightGen application. We examined the quality of the weights by applying an analytical function to each source grid point, performing the interpolation using the generated weights and comparing the interpolated results at the destination grid with their correct values. We then calculated the minimum, maximum and mean relative errors.

The analytical function used in this exercise is a function of the grid point's coordinates:

$$1.0 + 0.01*height+cos(lat)^2 * cos(2*lon)$$

where (*lon*, *lat*, *height*) is the coordinate of the given grid point and *height* is in kilometers. The results are shown in Table 1.

Table 1 The relative interpolation errors

	IPE->WAM	WAM->IPE
Number of weights	5630988	13163776
Mean Errors	0.0091819	0.0041149
Min Errors	6.9364e-06	9.0298e-06
Max Errors	0.057948	0.020084

We observed about1.0e-2 mean relative interpolation error in both directions. This relative error is higher than typical cases in the ESMF 2D test suite. In our 2D test cases, the mean relative errors are in the range of 1.0e-4 and 1.0e-7 using a similar analytical function. Upon further examination of the weights from the IPE grid to the WAM grid, we found that the higher errors are concentrated around the geomagnetic equator and at the lower altitude layers. Figure 6 is a 3D diagram showing all the destination grid points that have a 0.05 or higher relative interpolation errors.

From Figure 2, you can see that the mesh cells close to the geomagnetic equator area are very wide (about 500 km, or 4.5 degree in longitude) but very narrow. The heights of the 3D cells at low altitudes are only 2km. For 2D cells on a sphere, ESMF uses great circles to represent the edges of the cell. ESMF does not currently have a similar capability for 3D cells on a sphere and instead uses 3D cells with straight edges. Because of this, some of the destination nodes are mapped into different source cells than if the cells followed the curve of the sphere. This results in the higher interpolation errors for this spherical analytic function in the equatorial area, as shown in Figure 6.

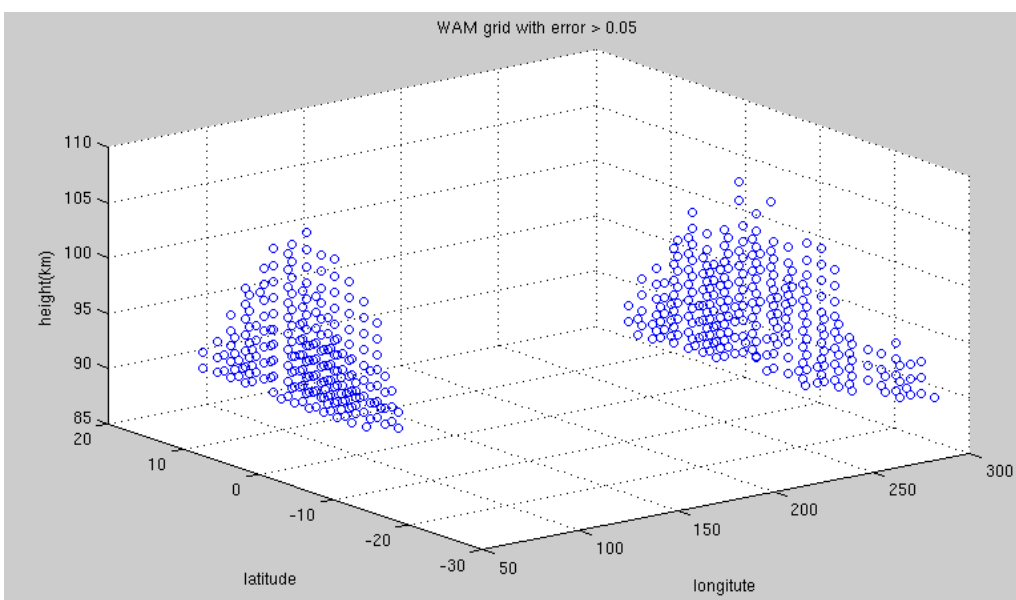

Figure 6 Distribution of large interpolation errors.

Performance Results

We performed a scalability benchmark using ESMF_RegridWeightGen. The benchmark ran on Yellowstone using 1 to 512 processors. Timing routines were added in ESMF_RegridWeightGen to measure the timing of ESMF_FieldRegridStore(). We ran each regridding twice and the results are shown in Table 2 and Figure 7 (all the times are in seconds).

Table 2 The ESMF_FieldRegridStore() time on Yellowstone (in seconds).

#process	IPE->WAM	IPE->WAM	WAM->IPE	WAM->IPE
1	124.082	124.013	139.677	139.765
2	82.201	82.892	87.577	88.21
4	50.936	51.02	47.929	48.153
8	30.835	30.924	28.988	28.988
16	18.438	18.463	16.419	16.389
32	12.828	12.849	9.678	9.685
64	8.865	7.225	6.263	6.234
128	4.019	4.004	4.271	4.271
256	2.327	2.312	2.447	2.424
512	1.487	1.447	1.43	1.439

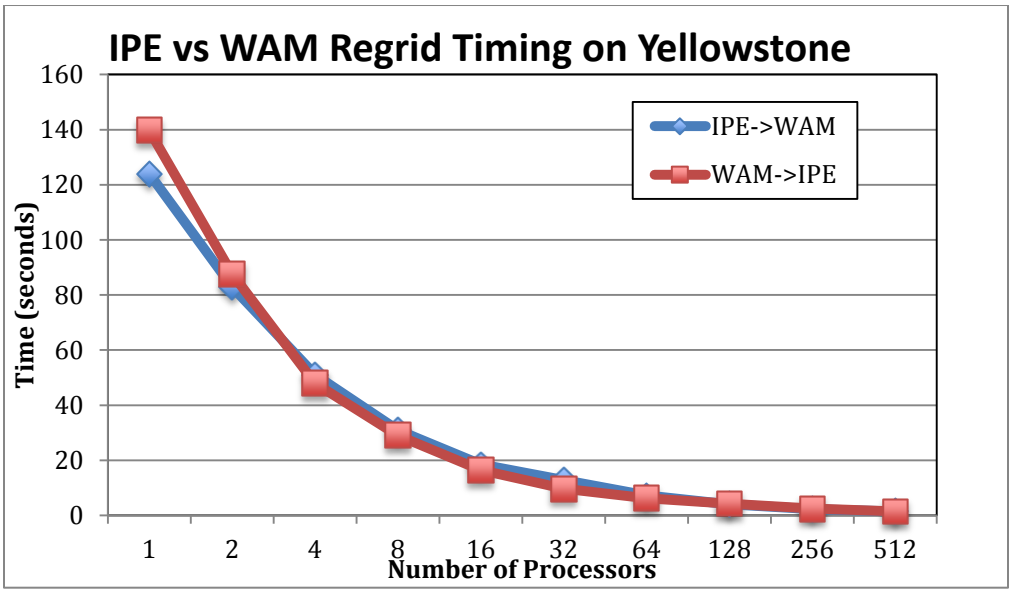

Figure 7 The ESMF_FieldRegridStore timing on Yellowstone

Remaining Tasks

There are several outstanding tasks yet to be accomplished before we can perform the grid remapping between the IPE and the WAM models while they run.

- Assess the initial measurements of performance and quality with SWPC staff.
- Enable the vertical interpolation weights to be updated without updating the horizontal weights, and generate an update to this report with the new performance results. From the performance benchmark, it takes about 1.4 seconds to perform the weight generation on 512 processors.
- Improve the interpolation weight quality by implementing the great circle mapping in ESMF for the 3D meshes, if the current accuracy does not meet the application requirements.
- Construct the ESMF 3D meshes using the same decomposition as used in the IPE and the WAM models.

Future tasks may include wrapping the IPE model as an ESMF component for coupling to the WAM model.