Performance of the Spectral Element Method on Red Storm

Petroglyphs to Petaflops
CUG - Albuquerque
May 2005

Mark Taylor
Bill Spotz
Sandia National Laboratories

Aime Fournier
Steve Thomas
Henry Tufo
National Center for Atmospheric Research

National Nuclear Security Administration

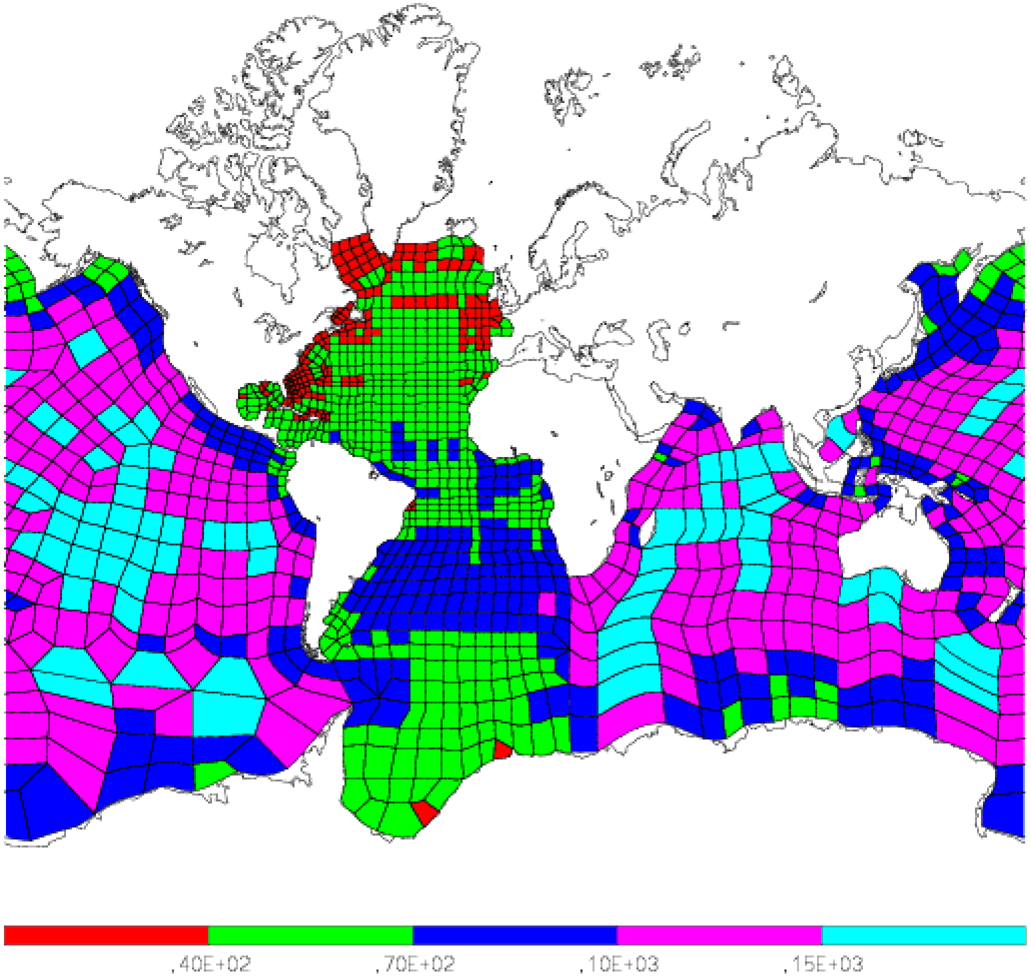
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company,
for the United States Department of Energy's National Nuclear Security Administration
under contract DE-AC04-94AL85000.

Sandia National Laboratories

Outline

- Overview of the Spectral Element Method for Atmospheric Modeling (SEAM)
- 2D and 3D test results
- Performance on ASCI-Red (9K CPUs), BG/L (8K CPUs) and Red Storm (28 CPUs)
- Petaflop performance estimates

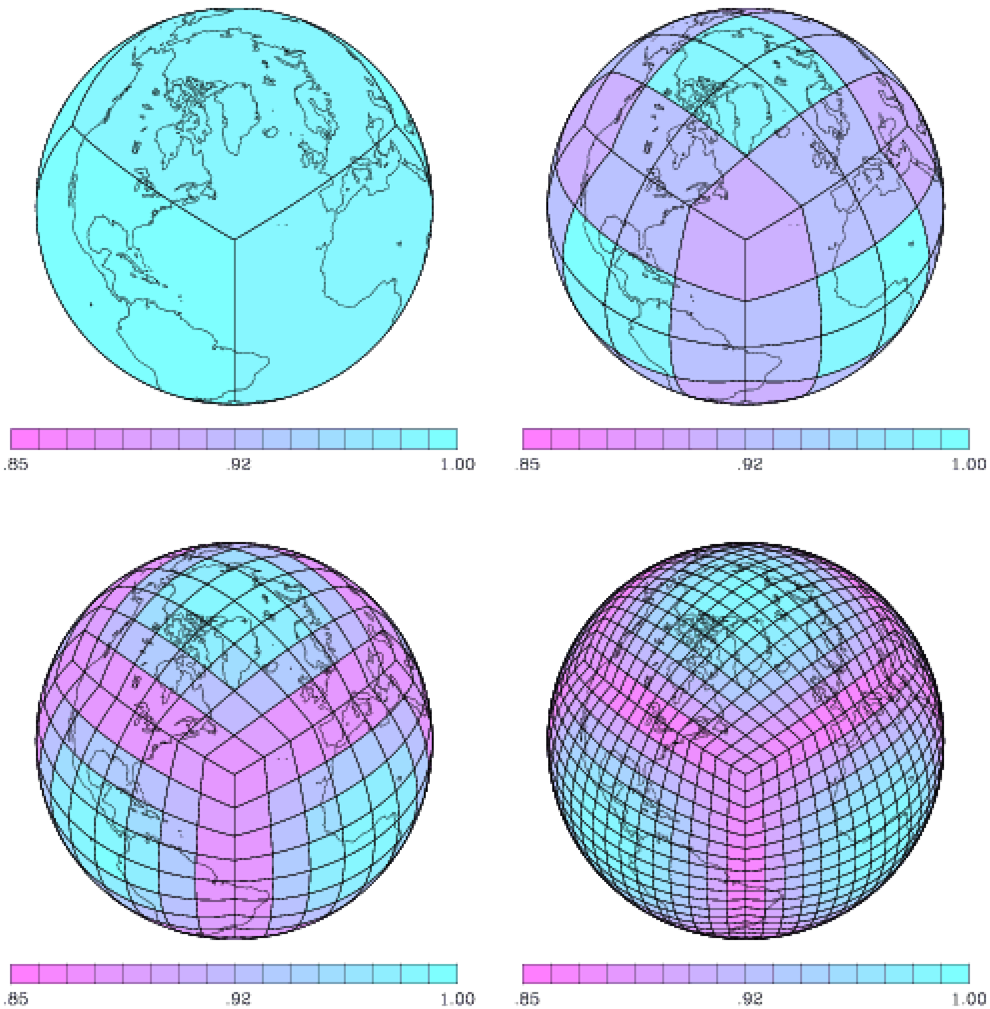
Spectral Elements on the Sphere
SEOM



Iskandarani et al., JCP 2003

Sandia National Laboratories

Spectral Elements on the Sphere



- No Pole Problems
  - Quasi-uniform resolution
  - No CFL problems
- Excellent accuracy
- Excellent parallel scalability

Shallow Water Equations
2D Flow on the surface of the sphere

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} + f \hat{k} \times \boldsymbol{u} + g \nabla (h + h_s) = 0$$

$$\frac{\partial h}{\partial t} + \nabla \cdot (h u) = 0$$

$\boldsymbol{u}$ = velocity field
h_s = surface height (topography)
h = atmosphere thickness

Shallow Water Equations
Integral Formulation

$$\int_D \frac{\partial h}{\partial t}\phi \, dA = -\int_D \nabla\cdot(h u)\phi \quad dA$$

Decompose domain *D* into rectangular regions:

$$\sum_D \int_\square \frac{\partial h}{\partial t}\phi \, dA = -\sum_D \int_\square \nabla\cdot(h u)\phi \, dA$$

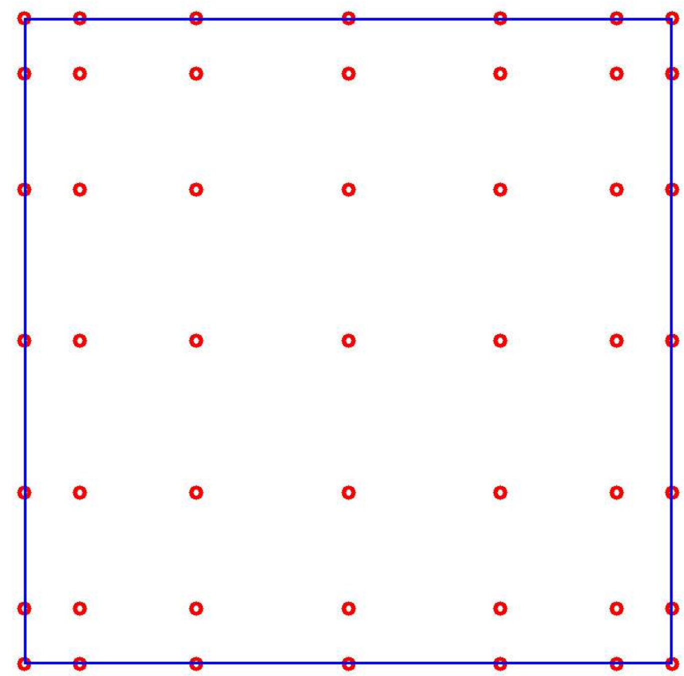
Spectral Element Discretization

- **Within each rectangle, estimate integrals by quadrature:**

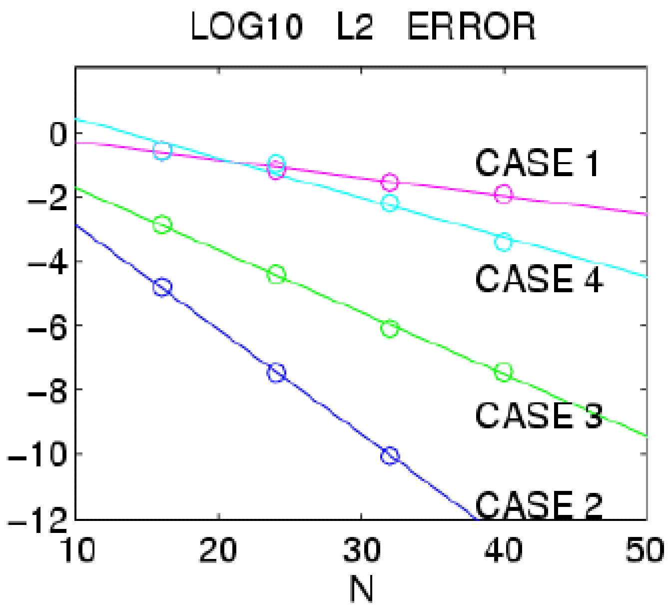
  $\{z_i\}$ = tensor product of Gauss-Lobatto points.

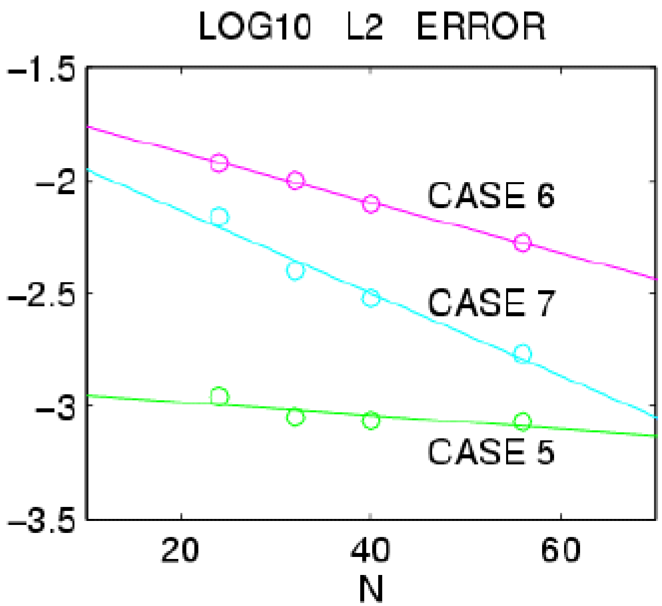
  $\{w_i\}$ = associated Newton-Cotes weights

$$\int_{\square} \frac{\partial h}{\partial t} \phi \, dA \simeq \sum_i w_i \frac{\partial h}{\partial t}(z_i)\, \phi(z_i)$$



Shallow Water Equations on the Sphere
p refinement with 6 elements

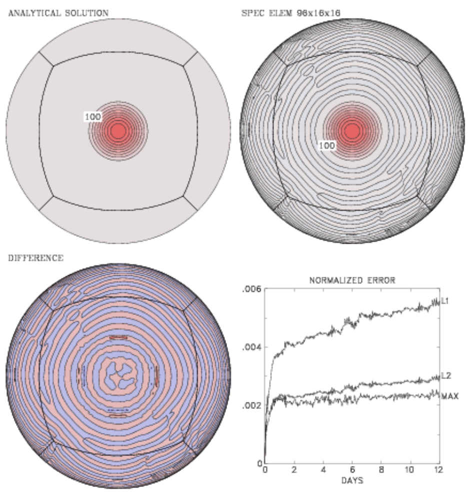


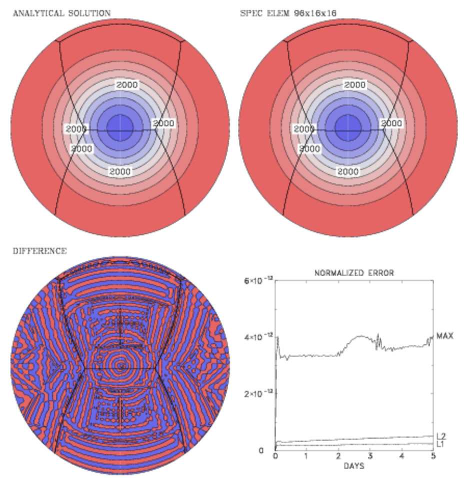


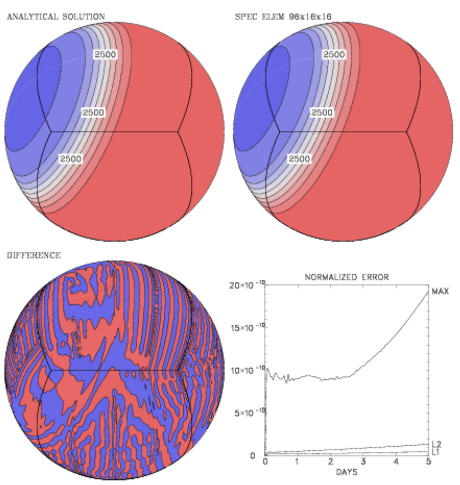
Williamson, Drake, Hack, Jakob, Swarztrauber, *A standard test set for the numerical approximations to the shallow water equations in spherical geometry*, J. Comput. Phys., 1992.
Taylor, Tribbia, Iskandarani, J. Comput. Phys., 1997

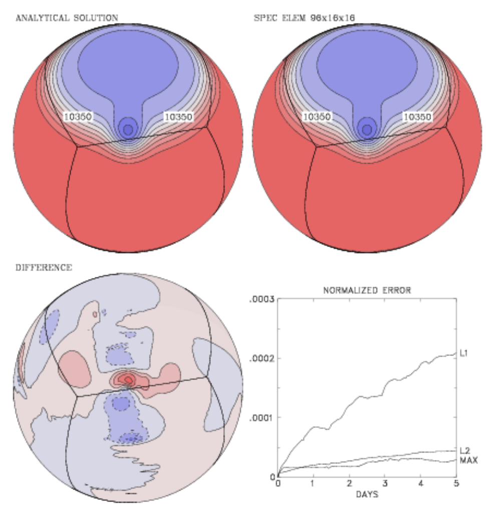
Sandia National Laboratories

Shallow Water Equations on the Sphere
Tests 1-4



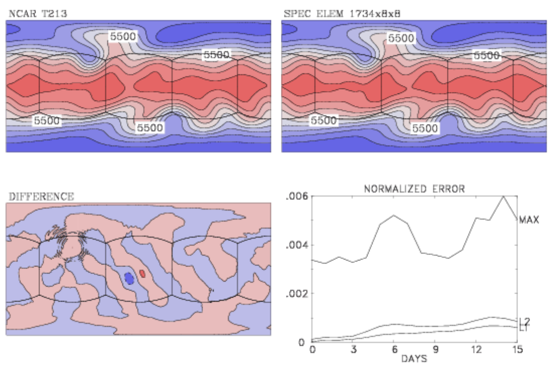


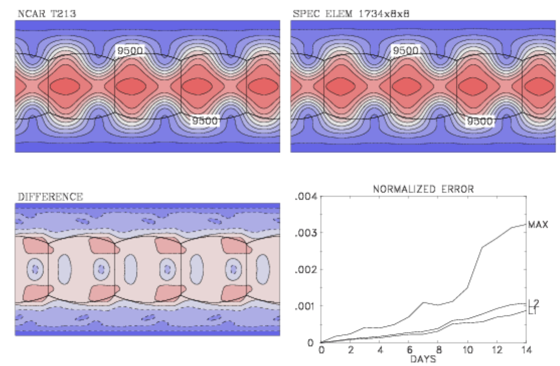


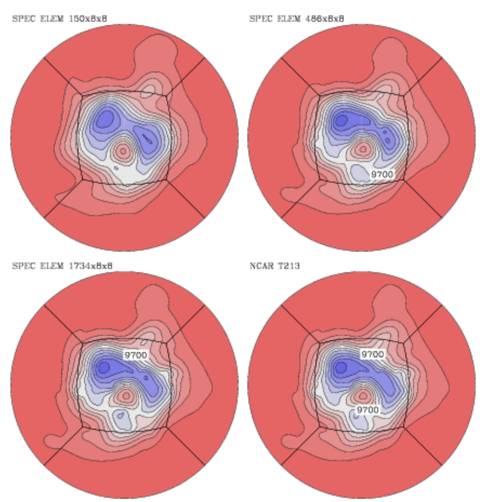


Sandia National Laboratories

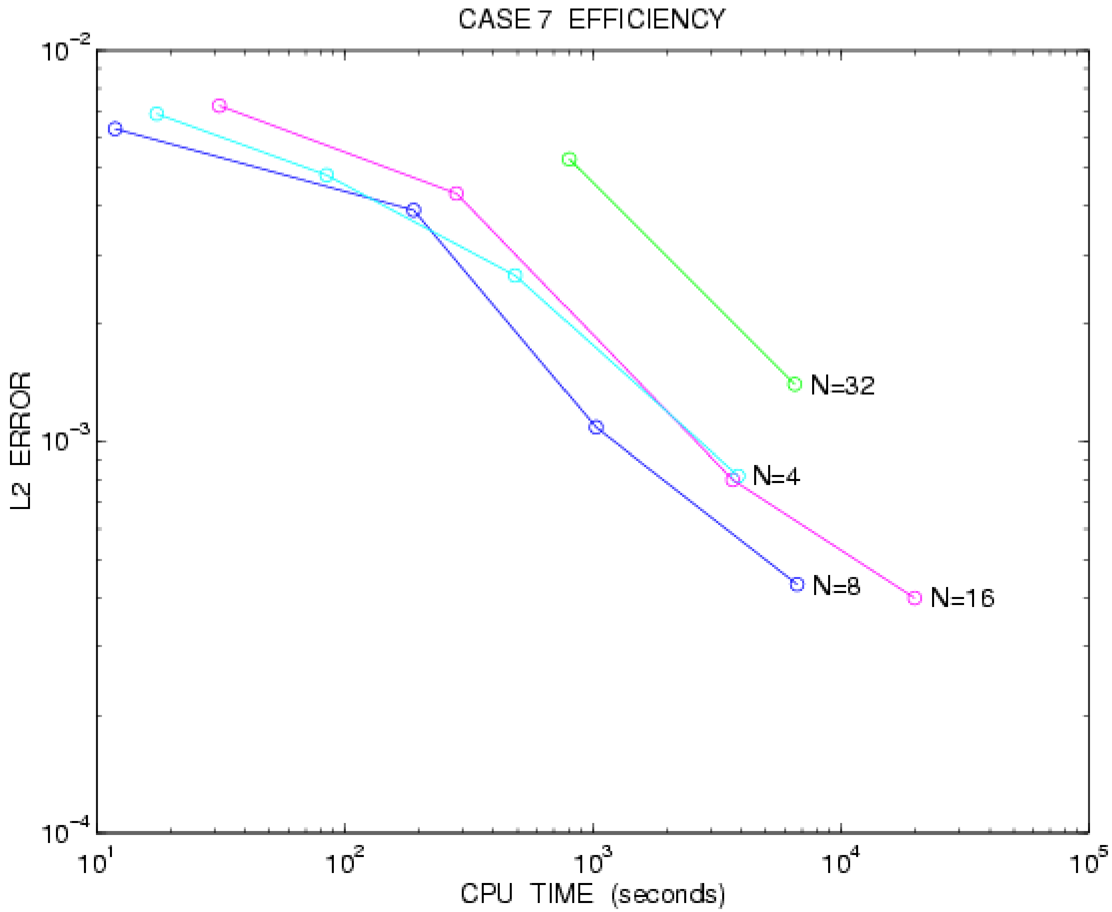
Shallow Water Equations on the Sphere
Test 5-7





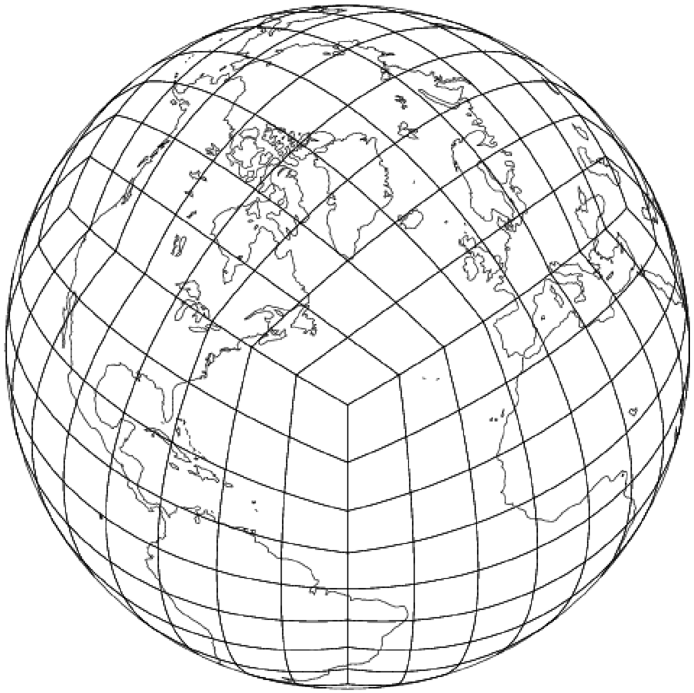


Shallow Water Equations on the Sphere
Test 7: p vs. h refinement



Sandia National Laboratories

Spectral Element Atmospheric Model (SEAM)

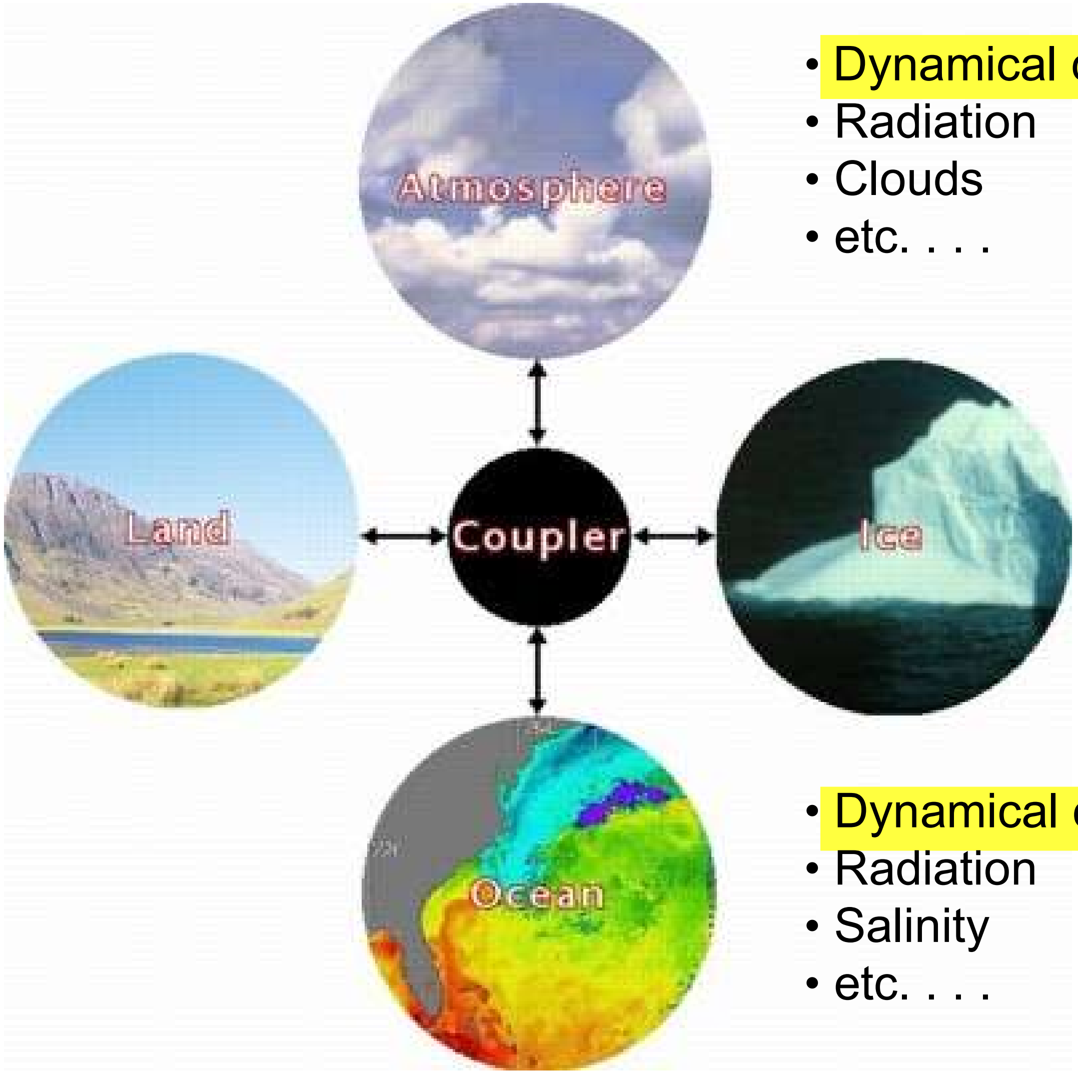


- Global Atmospheric Circulation Model
- Spectral elements used in horizontal directions
- Finite differences used in vertical/radial direction
- Two dimensional domain decomposition: each processor contains one or more elements and the vertical columns of data associated with those elements.
- Coupled to the Community Atmospheric Model (CAM) Physics package

•Taylor, Tribbia, Iskandarni, 1997; Taylor, Loft, Tribbia, 1998; Loft, Thomas, Dennis, 2001;
• Thomas, Loft, 2002; Thomas, Loft 2004; Fournier, Taylor, Tribbia 2004;

Sandia National Laboratories

Community Climate System Model



- Dynamical core
- Radiation
- Clouds
- etc. . . .

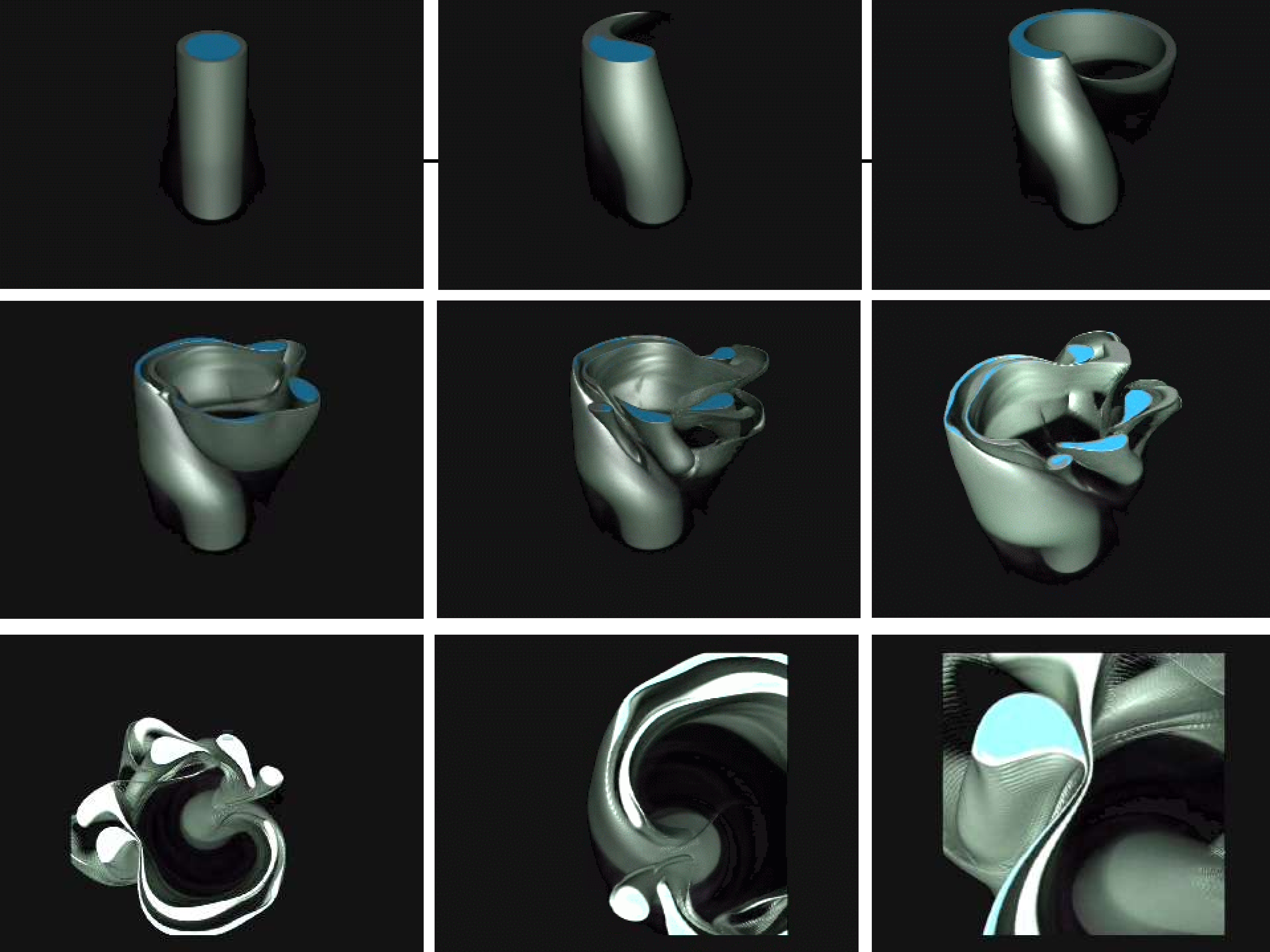
- Dynamical core
- Radiation
- Salinity
- etc. . . .

Polar Vortex

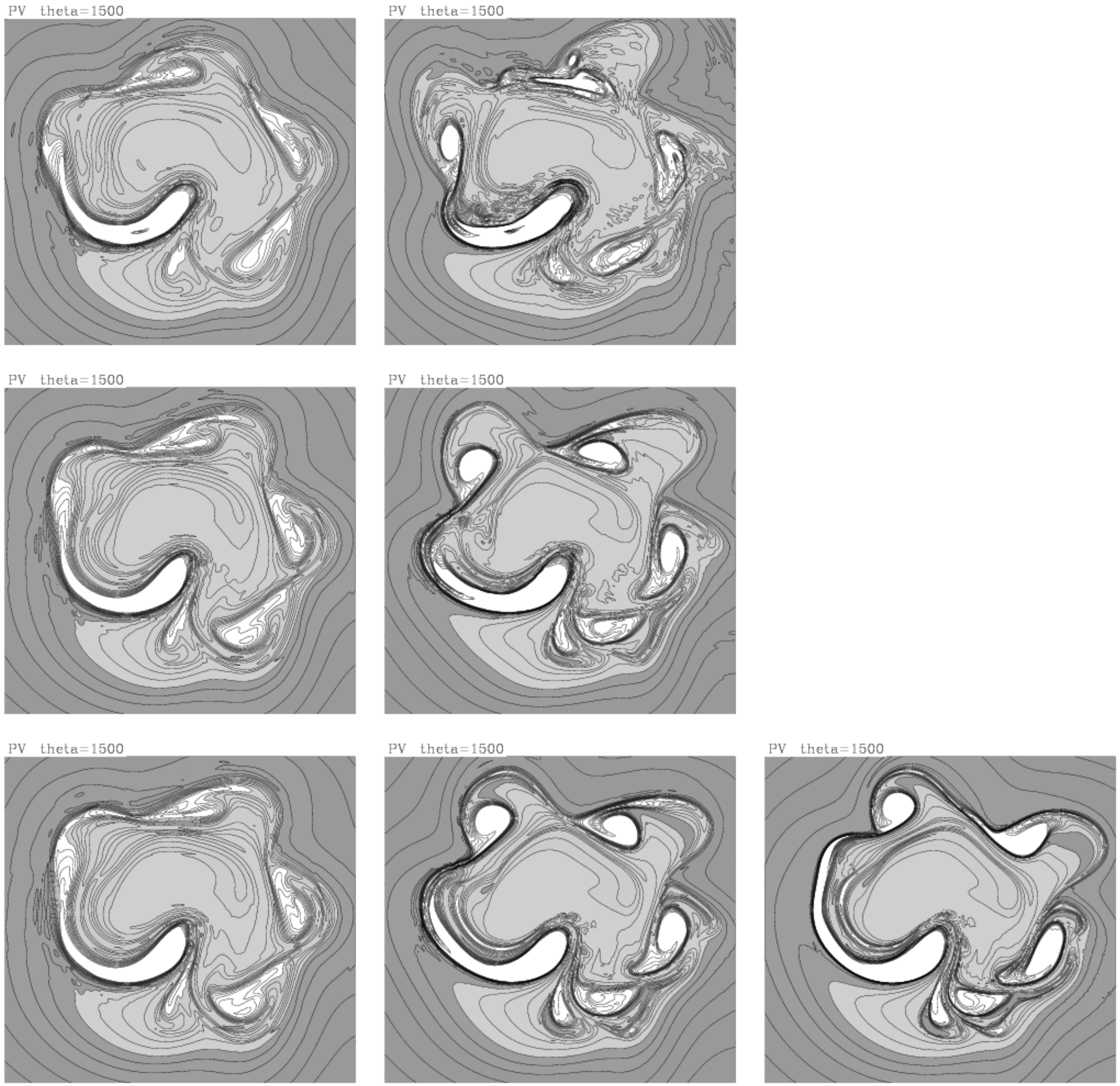
- Atmospheric Primitive equations
  - Dry dynamics
  - Euler Fluid Dynamics Equations (rotating frame)
  - Hydrostatic approximation
- Forced at the lower boundary to simulate an upward propagating Rossby wave
- Numerical Statistics
  - 36km grid spacing, 200 levels in the vertical
  - 88M grid points, 2 days on 256 CPUs (IBM SP/NCAR, SNL - Linux Cluster)

- Polvani, Saravanan, *The three-dimensional structure of breaking Rossby waves in the polar wintertime stratosphere*, J. Atmos Sci., 2000
- Dennis, Fournier, Spotz, St.-Cyr, Taylor, Thomas, Tufo, *High Resolution Mesh Convergence Properties and Parallel Efficiency of a Spectral Element Atmospheric Dynamical Core*, to appear, IJHPCA special issue on Climate Modeling Algorithms and Software Practice.

Sandia National Laboratories

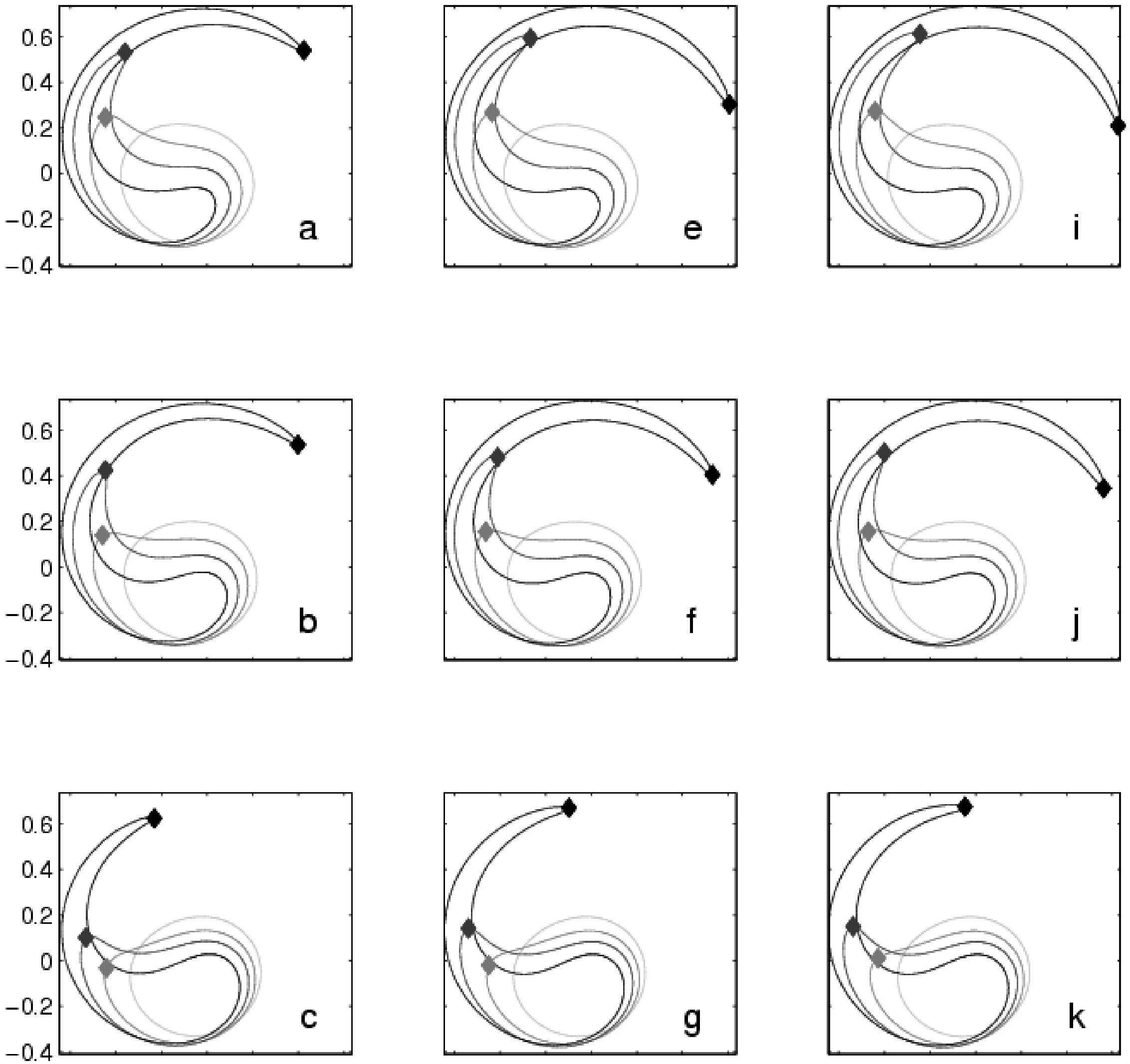


Polar Vortex



Sandia National Laboratories

Polar Vortex



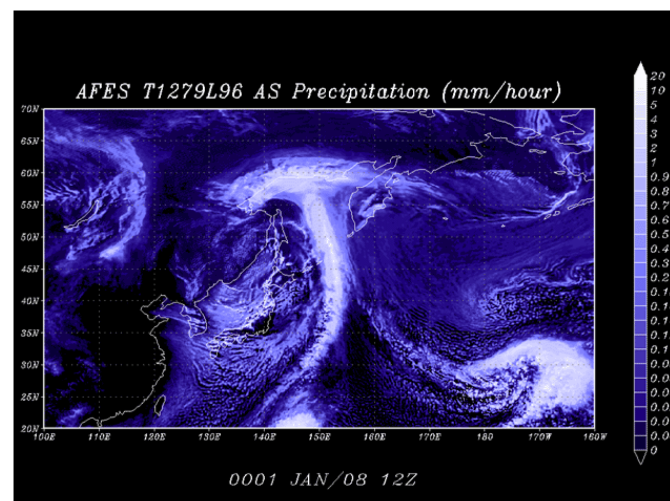
Goal: Demonstrate 10km capability on MPPs

- DOE SCaLeS Report
  - "An important long-term objective of climate modeling is to have the spatial resolution of the atmospheric and oceanic components both at ~1/10° (~ 10 km resolution at the Equator)."
- Atmospheric Model
  - At 10km, the atmosphere will be the dominant component of a coupled model.
  - 10km is necessary to resolve regional detail of temperature and precipitation important for local and social impacts of climate change (land use, water resources, agriculture, forest management, conflict due to environmental scarcity)
  - 10km capability would also allow regional forecast models to be replaced with a single global forecast model. (NOAA's National Hurricane Center predicts hurricane landfall using a regional model with a 10km grid.)

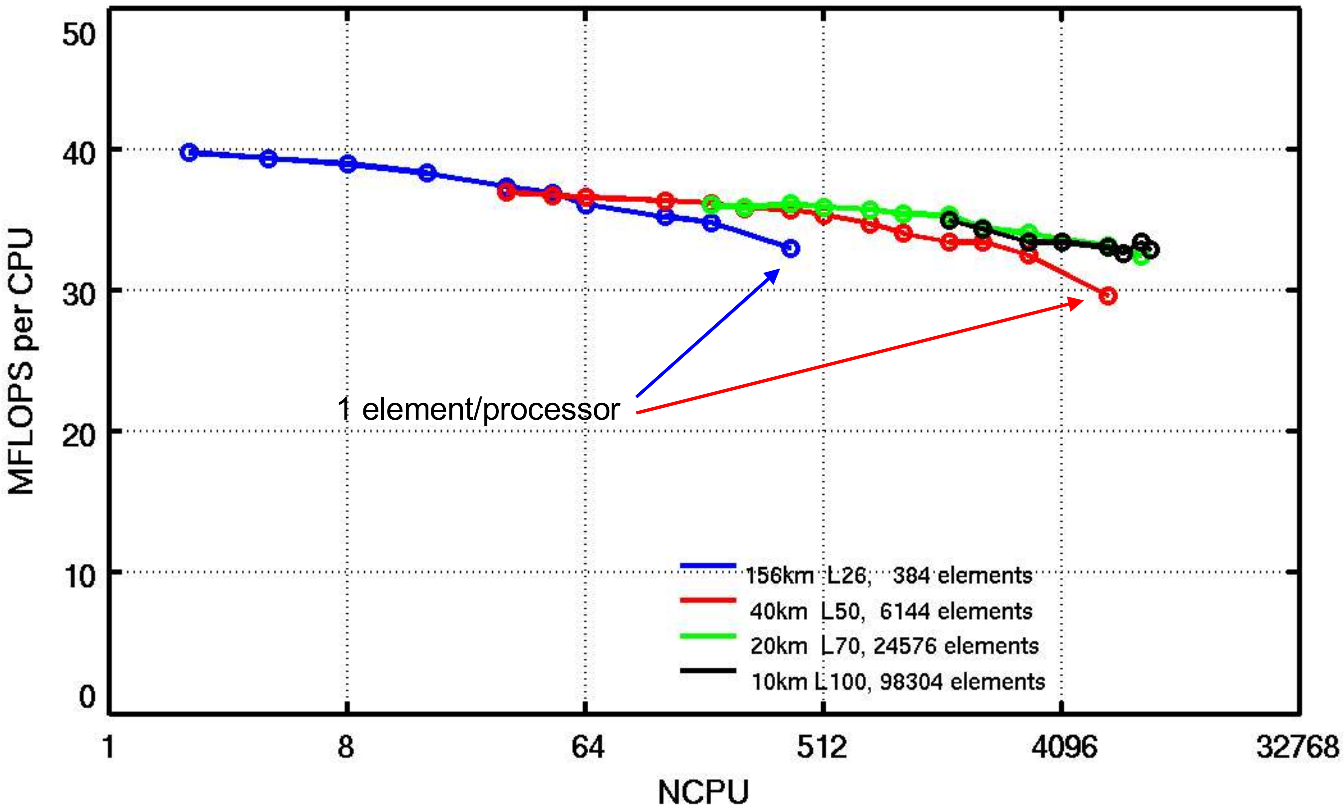
Sandia National Laboratories

10Km on the Earth Simulator

- 640 SMP Nodes, each with 8 vector processors
- AFES Atmospheric Model
  - Global Spectral Model (spherical harmonics)
  - Excellent vector performance (65% of peak on the Earth Simulator) ~24 TF
  - This performance obtainable only up to 640 partitions (at 10km resolution)
  - Resolution: 10km 96L
  - Runs at 57x reality



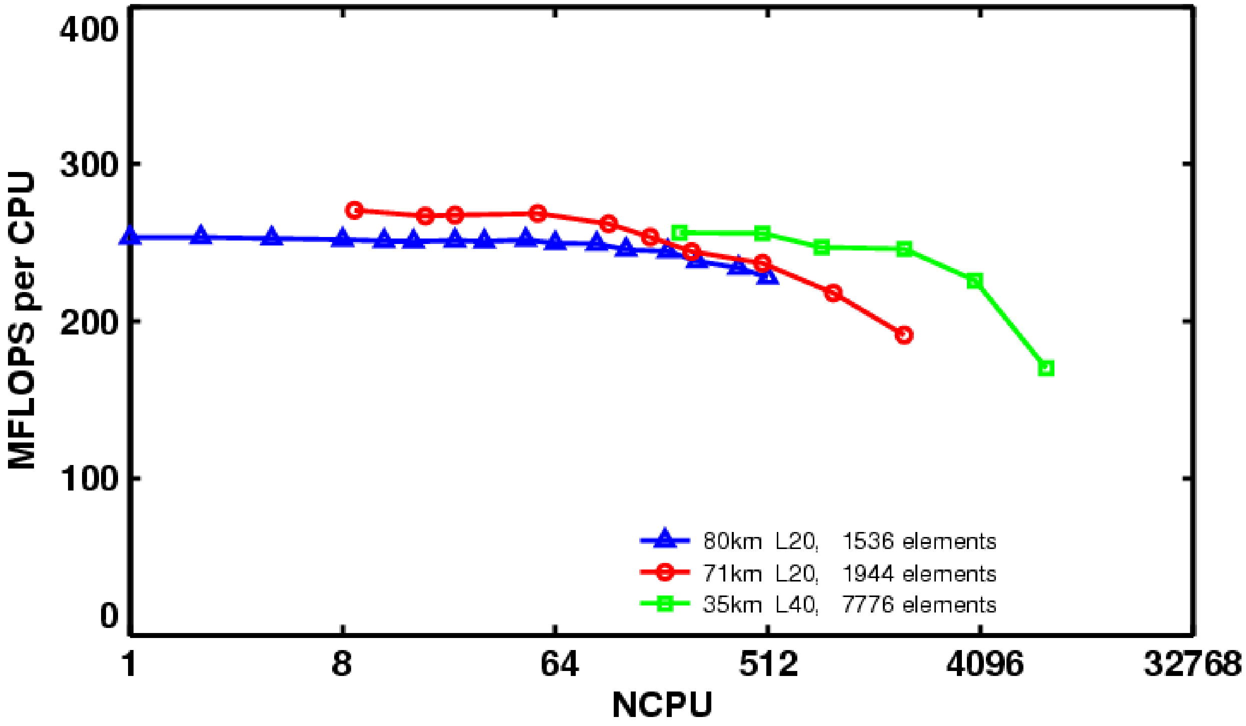
SEAM on ASCI Red



Performance of 4 fixed problem sizes, on up to 8938 CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.

Sandia National Laboratories

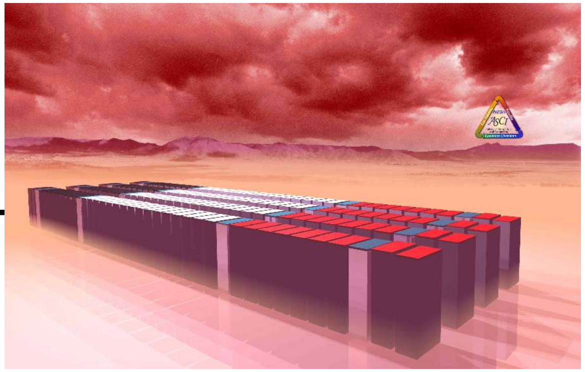
SEAM on BG/L

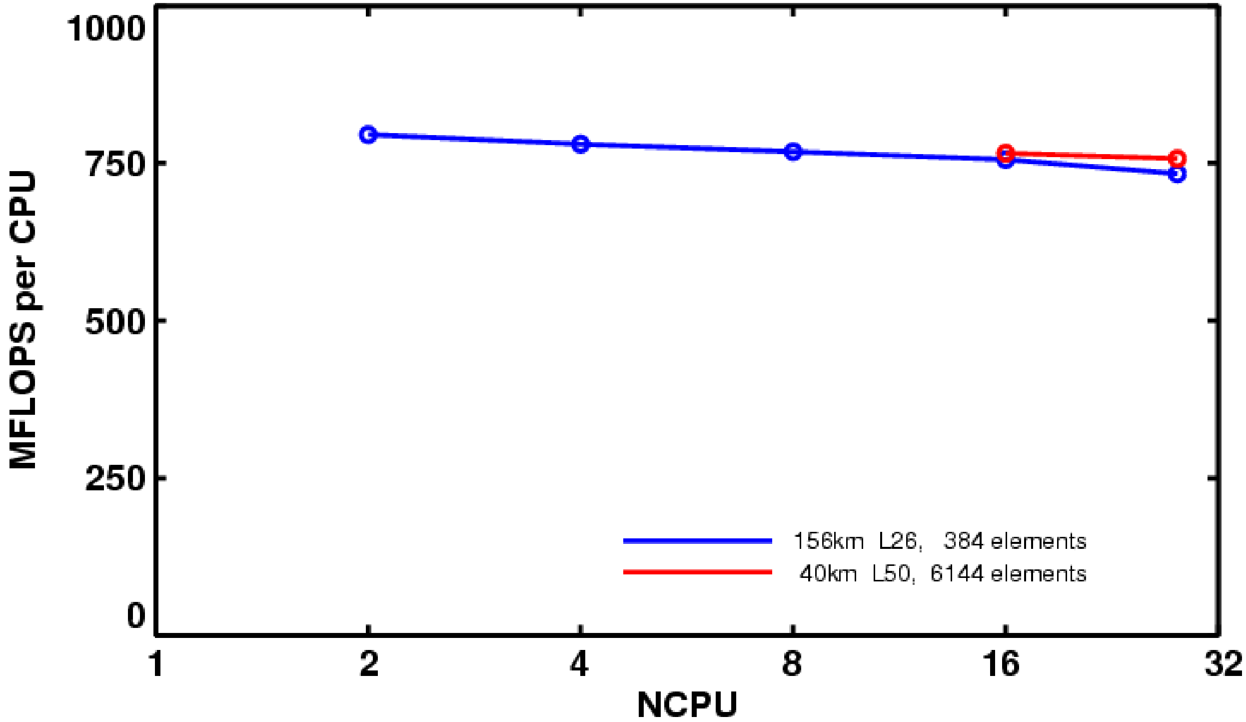


Performance of 4 fixed problem sizes, on up to 7776 CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.

Sandia National Laboratories

SEAM on Red Storm



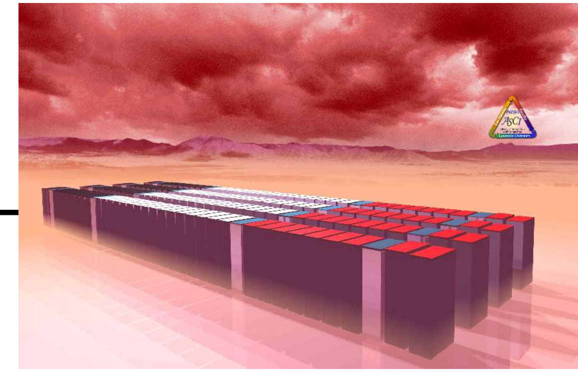


Performance of 2 fixed problem sizes, on up to 28 CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.

Thanks to Sue Kelly for running these benchmarks on a Red Storm Test system.

Sandia National Laboratories

SEAM on Red Storm



- 10 Km Performance Requirements for 1X Reality
  - 98,304 Elements, 100 Levels: 0.5B grid points
  - Explicit: 337 GFLOPS
  - Semi-Implicit/OIFS: 110 GFLOPS

- Red Storm Projection
  - AMD Opteron, 64bit, 4GF Peak
  - Assume 750 MFLOPS/cpu, ASCI-Red-like scalability: SEAM ~8TF
  - 10km/100L: Integrate at 23-72 model days per day

Sandia National Laboratories

SEAM on a PetaFlop Computer

- Red Storm communication/computation balance
- 5x more CPUs (50,000)
- 5x faster CPU and memory bandwidth (20GF Peak)
- SEAM:
  - Demonstrated scalability to 9000 CPUs
  - Demonstrated scalability to 1 element per CPU
  - Estimate 10km problem should scale to 98,000 CPUs
- SEAM: ~200TF
- 10km/100L: Integrate at 600-1800 model days per day

Conclusions

- SEAM scales to thousands of CPUs on mesh-interconnect supercomputers
- Red Storm has similar computation/communication balance as ASCI-Red
- Red Storm performance 20x improvement over ASCI-Red.
- Red Storm achieves performance competitive with the Earth Simulator.