Massively Parallel Performance of the HOMME Spectral Element Atmosphere Model

The 8th International Workshop on Next Generation Climate Models for Advanced High-Performance Computing Facilities

February 24, 2006

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In collaboration with NCAR Scientific Computing Division

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A Little Background…

- Sandia has a long history as a leader in advanced, high-performance **computing**
- A significant percentage of Sandia's scientific applications are based on **finite elements**
- Historically, Sandia computing has focused on **engineering**-related problems and has had only minimal involvement in climate modeling
- I joined Sandia in 2001 after 5+ years at **NCAR** (atmospheric dynamical cores)
- **Mark Taylor** joined Sandia in 2004 after 5+ years at LANL (ocean modeling) and 5+ at NCAR (**SEAM**)
- HOMME/SEAM **element**-based numerical method and **scalability** made it attractive for a collaborative effort

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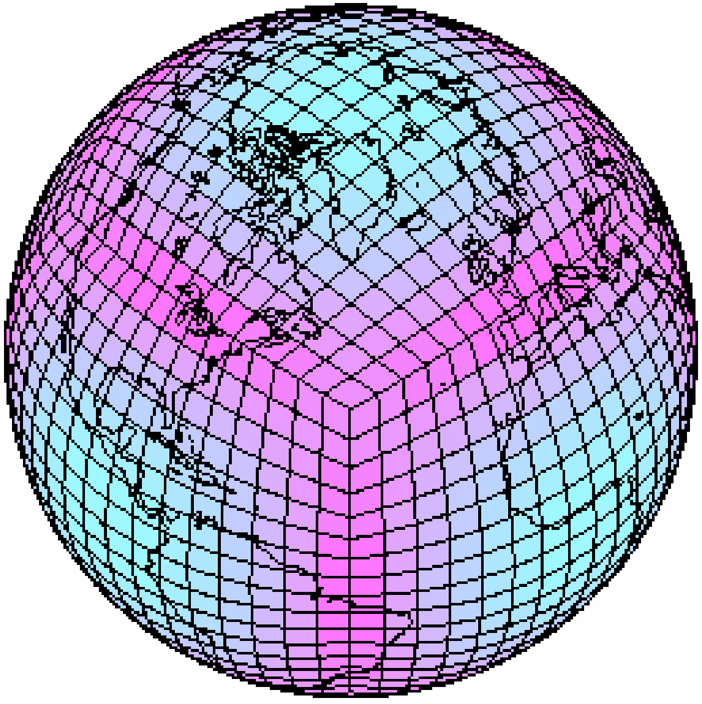
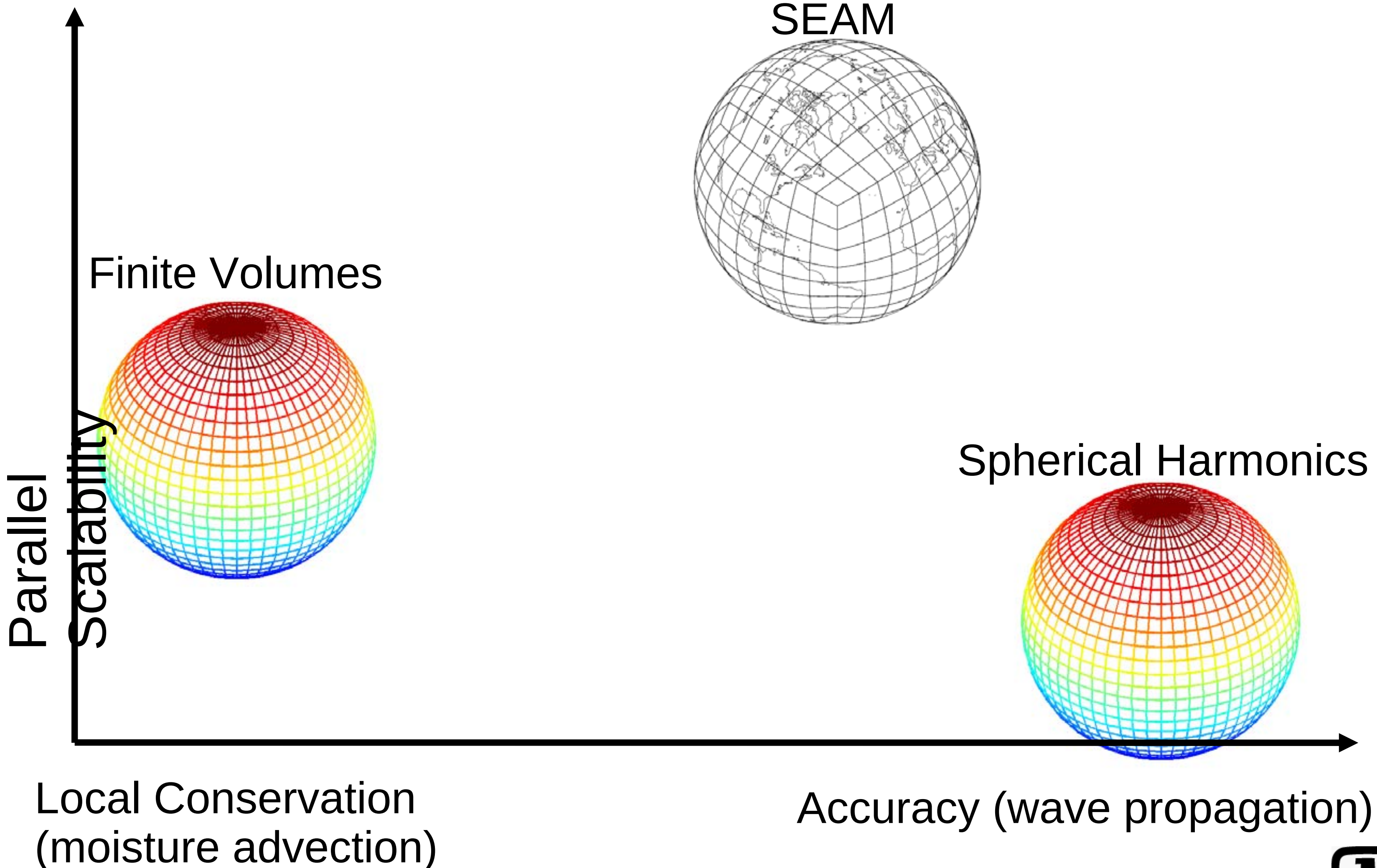
SEAM: Spectral Element Atmosphere Model



- Atmospheric global circulation model (GCM)
  - NCAR/DOE CHAMMP
- Quadrilateral spectral elements in horizontal
- Finite differences in vertical
- Cubed sphere, 2D domain decomposition
- 6 transforms between spherical and local cartesian coordinates
  - No pole problem
  - Edge conditions
- 2001 Gordon Bell Honorable Mention

Atmospheric Dynamical Cores

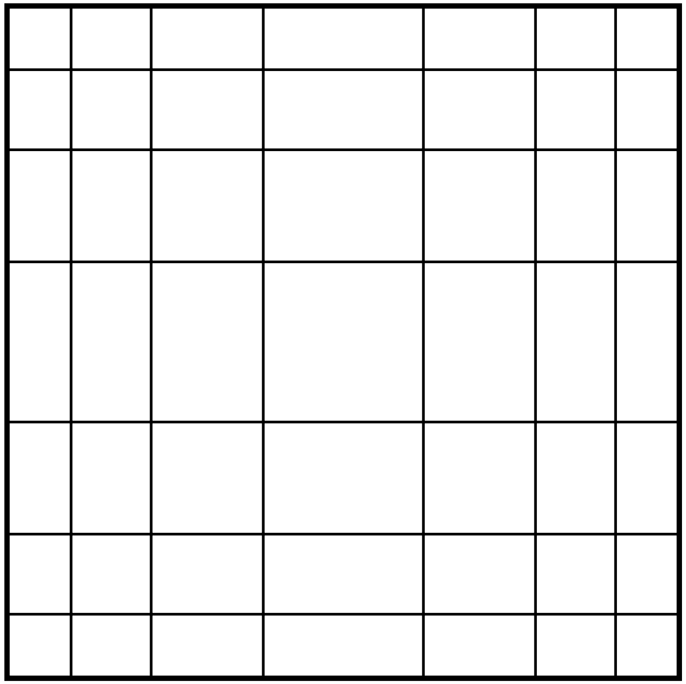


HOMME / SEAM

- **Accuracy:** can achieve same accuracy as spherical harmonic models.
- **High order** representation allows for high order scale selective dissipation (like hyper viscosity used in S.H.)
- **Unstructured Grid:** Can handle AMR
- **Unstructured Grid:** No pole problem, so excellent parallel scalability
- **Unstructured Grid:** New challenges for existing physics parameterizations?
- **Local Conservation:** Less oscillatory than S.H., but does not have exact local conservation (DG?)

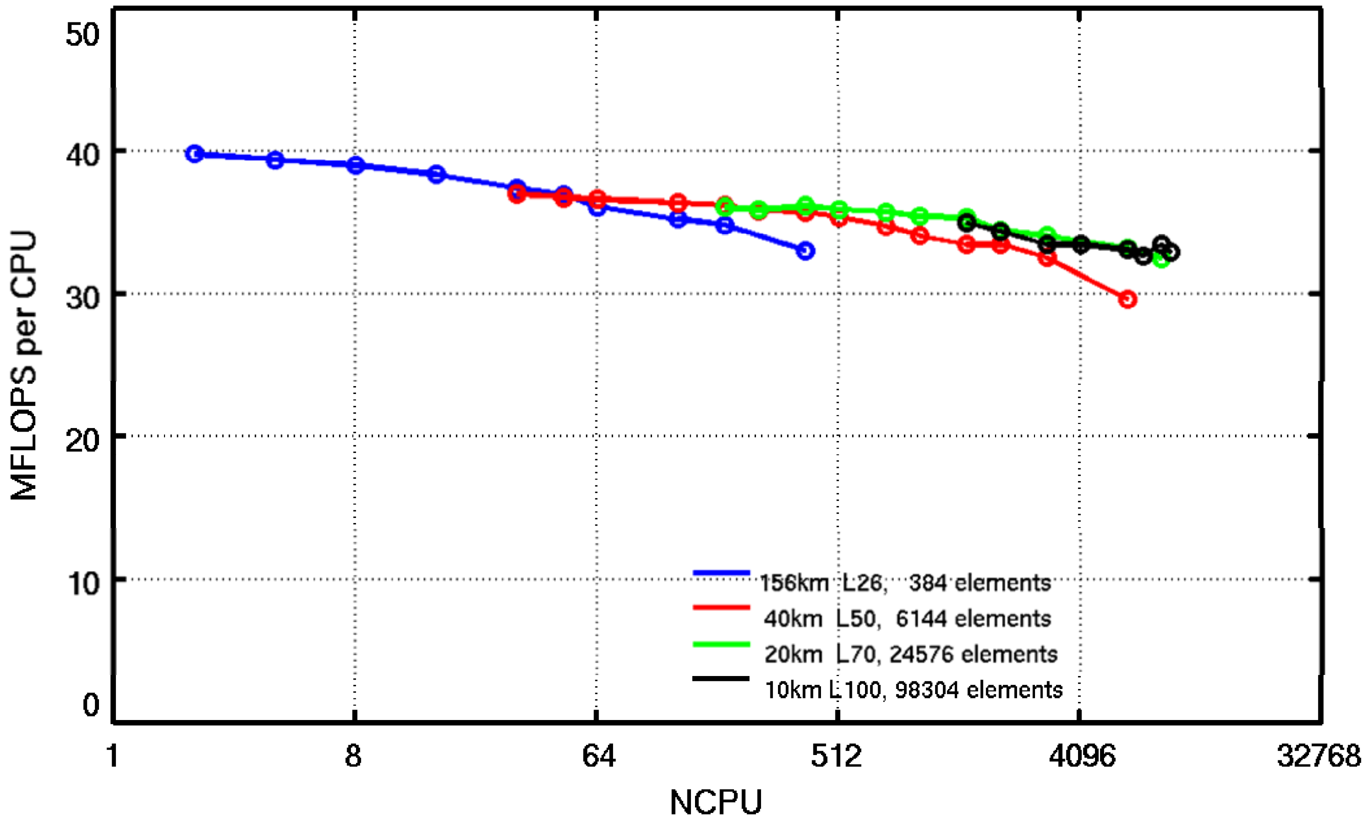
Why do Spectral Elements Scale Well?

- Scalability depends on doing enough computational work relative to communication
- For fixed-resolution problems, this is always a losing battle: as processors ↑, communication ↑, computational work ↓
- Even as spectral elements approach their granularity limit, they still represent a reasonable amount of computational work
- 1 mat-vec represents 64x(64+63)=**8128** FLOPS/element
- Equivalent FV patch: 64x(9+8)= **1088** FLOPS/patch



How Well Does SEAM Scale?

Janus



Spotz, "Performance Results and Analysis of the Spectral Element Method on the Sphere at Sandia," presented at the *2004 Workshop for the Solution of PDEs on the Sphere*, Yokohama, Japan, July 21, 2004.

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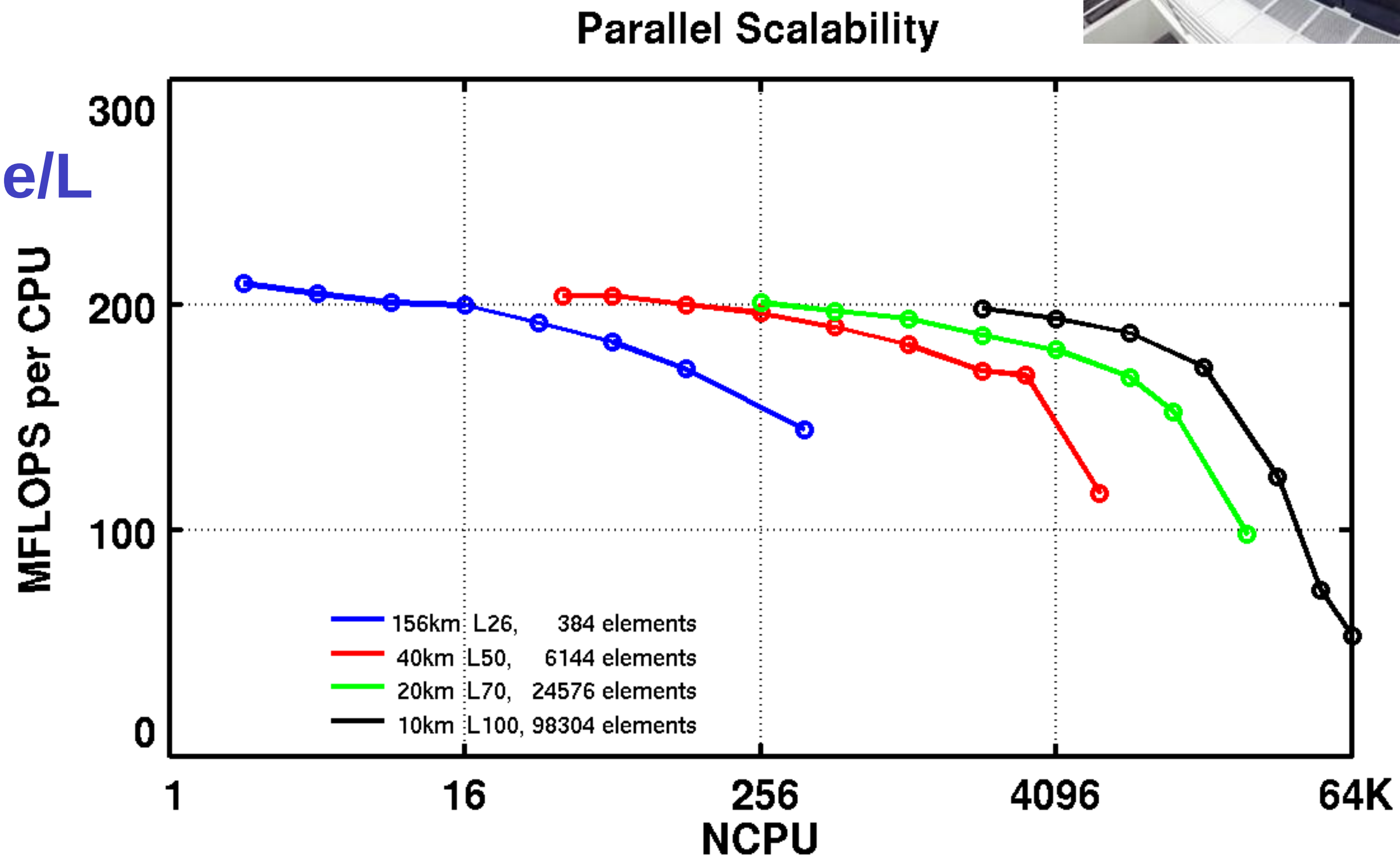
How Well Does SEAM Scale?

BlueGene/L



Dennis, Fournier, Spotz, St.-Cyr, Taylor, Thomas, Tufo, "High Resolution Mesh Convergence Properties and Parallel Efficiency of a Spectral Element Atmospheric Dynamical Core," *Int. J. High Perform. Comp. Appl.* special issue on Climate Modeling Algorithms and Software Practice

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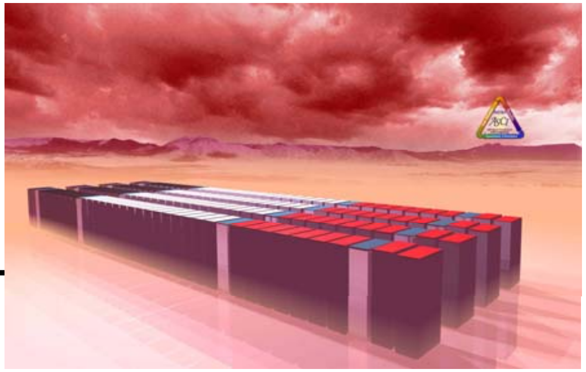
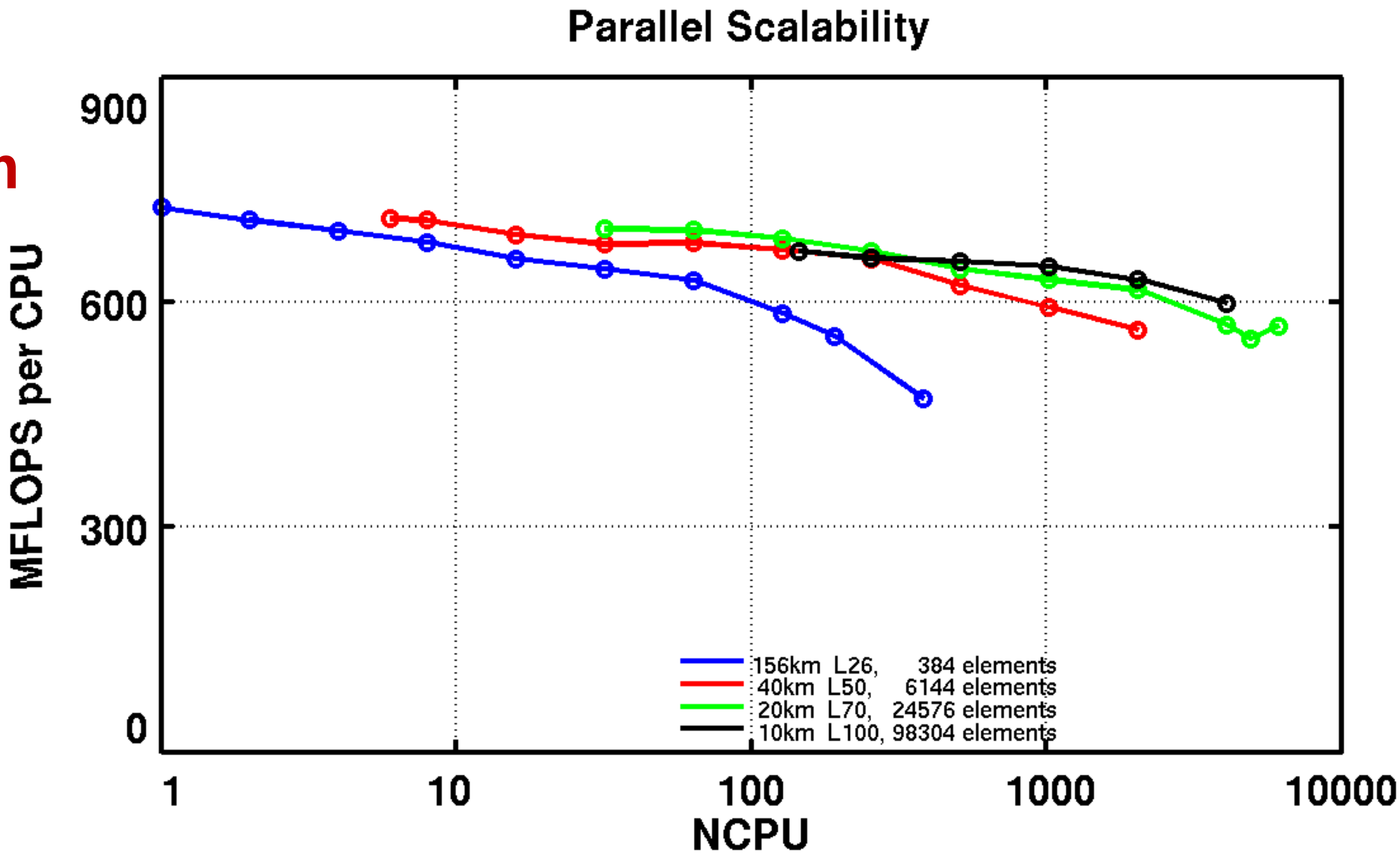
How Well Does SEAM Scale?



Red Storm



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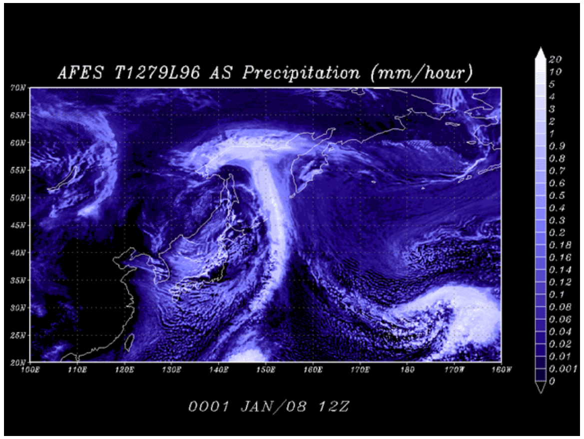
Integration Rates

- Atmosphere For Earth Simulator (AFES)
  - Global spectral model (spherical harmonics: Legendre transforms, all-to-all transpositions)
  - Full physics
  - 10km (24TF) 57 sim days/day



- Red Storm (SEAM)
  - Spectral elements: local computations and communications
  - Aquaplanet (reduced physics)
  - 40km (3TF) 7-30 sim years/day
  - 10km (5TF) 32-128 sim days/day

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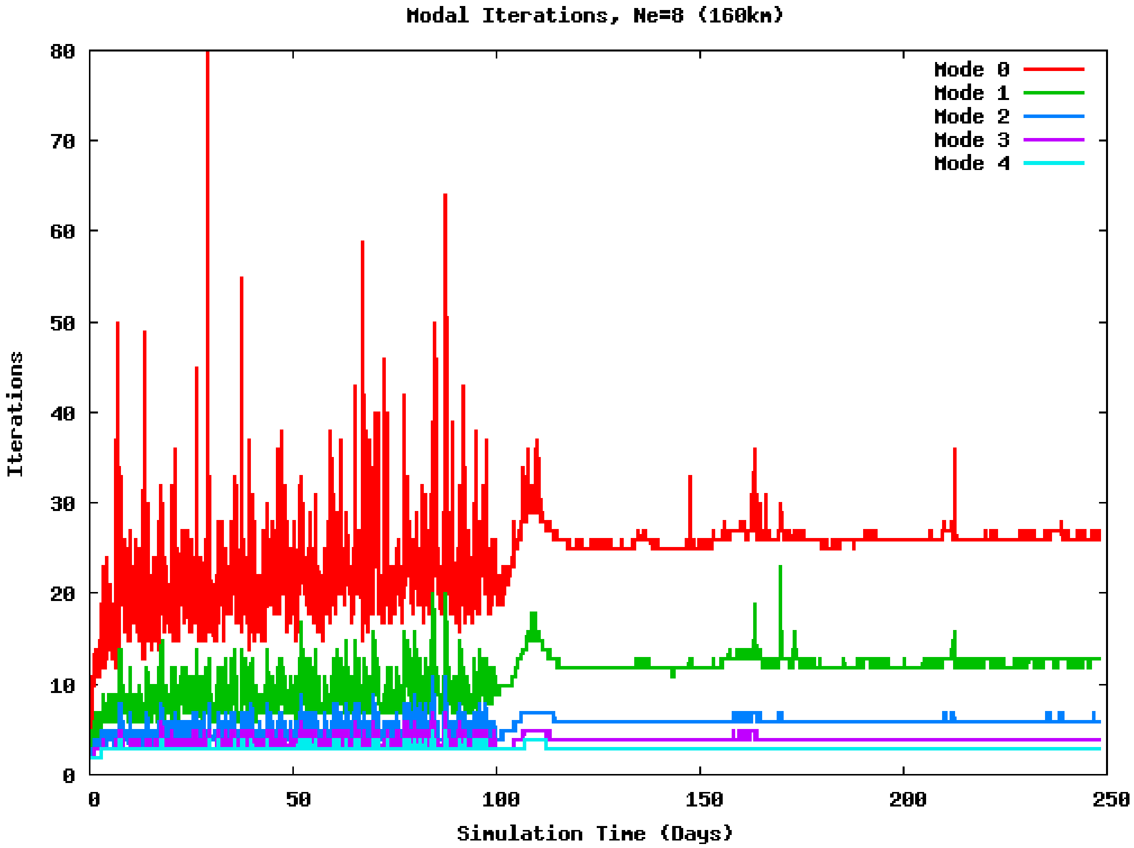
Why the Range of Integration Rates?

- Explicit vs. Semi-implicit time stepping
- Explicit (lower bound):
  - Small Δt for stability
  - Efficient numerical kernel
- Semi-implicit (upper bound…):
  - Larger Δt for stability (~x8)
  - Helmholtz solve: communication required every iteration
  - How many iterations?
- Research questions:
  - What is the best algebraic preconditioner for spectral elements?
  - What is the optimal Δt?
  - What is the best integration rate we can obtain?

Current Semi-Implicit Scheme

- 3D primitive equations
- Hydrostatic assumption
- Loosely coupled “stack” of shallow water equations
- Eigenmode decomposition in vertical direction (split semi-implicit)
  - For L levels, this is an L x L eigensystem
  - Results in L independent 2D systems to solve
  - Most energy & linear system solver work occurs in lowest eigenmodes
  - Decomposition is pre-processing step
  - Transforms: physical space ⇔ eigenspace
  - Quantity of interest: post-spinup average iterations for each eigenmode (function of resolution)

SEAM Split Semi-Implicit Iterations



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Description of Numerical Experiment

- For each resolution of interest
  - Run model until it reaches “solver equilibrium” (>100 days)
  - Obtain iteration profile (# iterations vs. eigenmode)
  - Hard-code the solver algorithm to perform these specified numbers of iterations (ignoring convergence)
- For each processor count of interest
  - Run short (5 time step) performance experiments for semi-implicit and explicit
  - Compute ratio of integration rates: semi-implicit/ explicit

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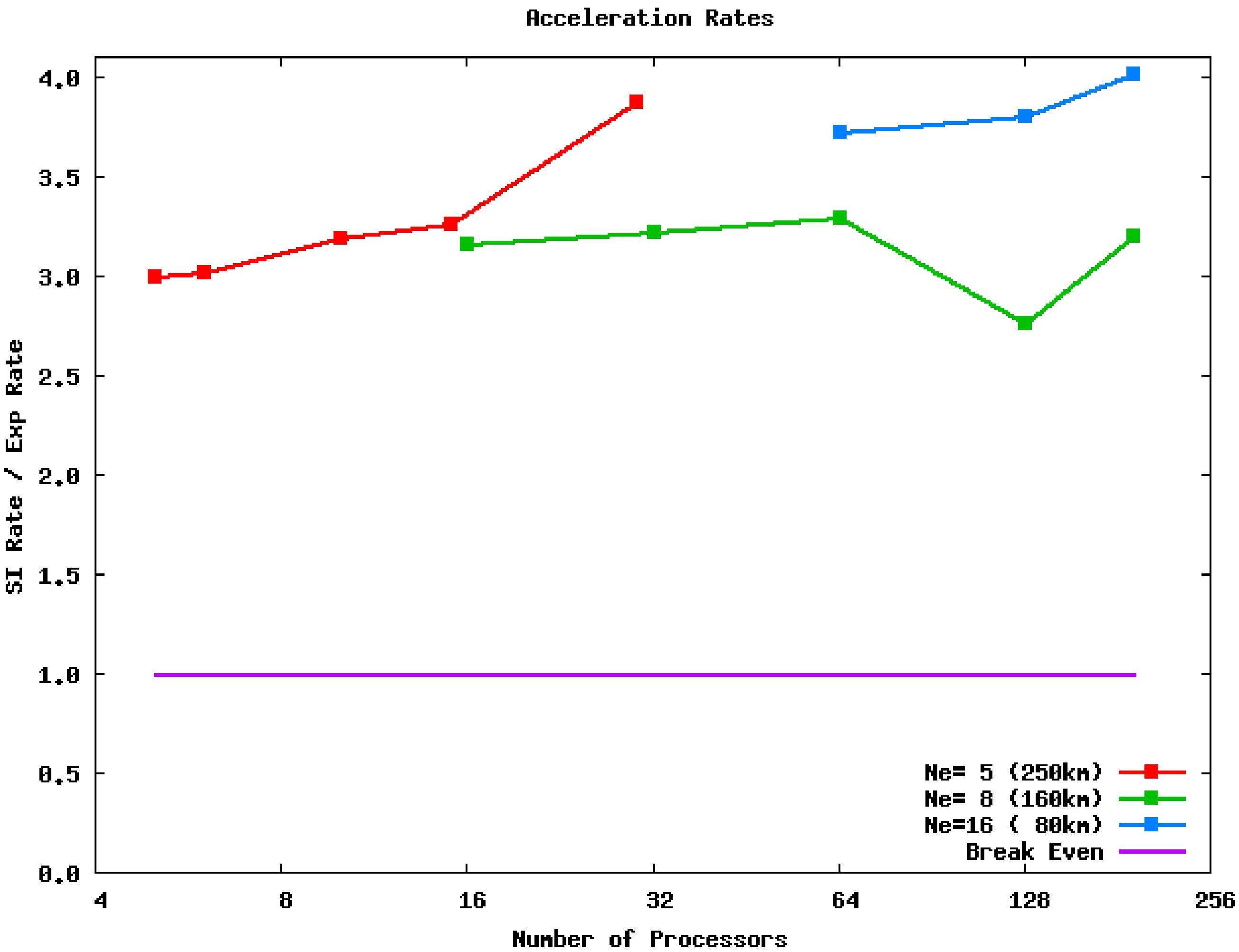
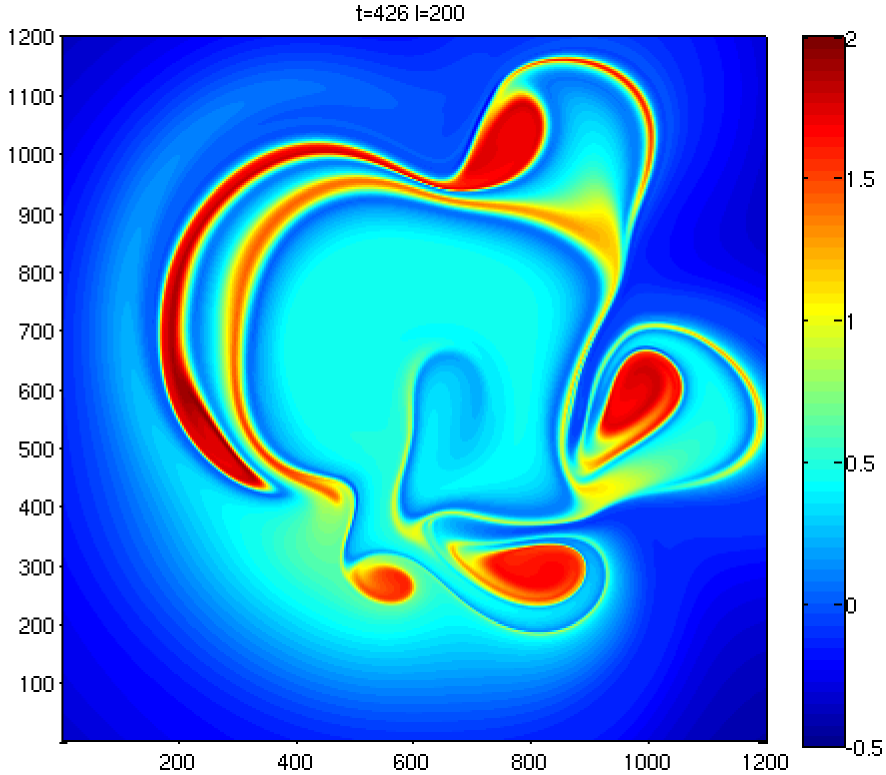
SEAM Split Semi-Implicit Acceleration

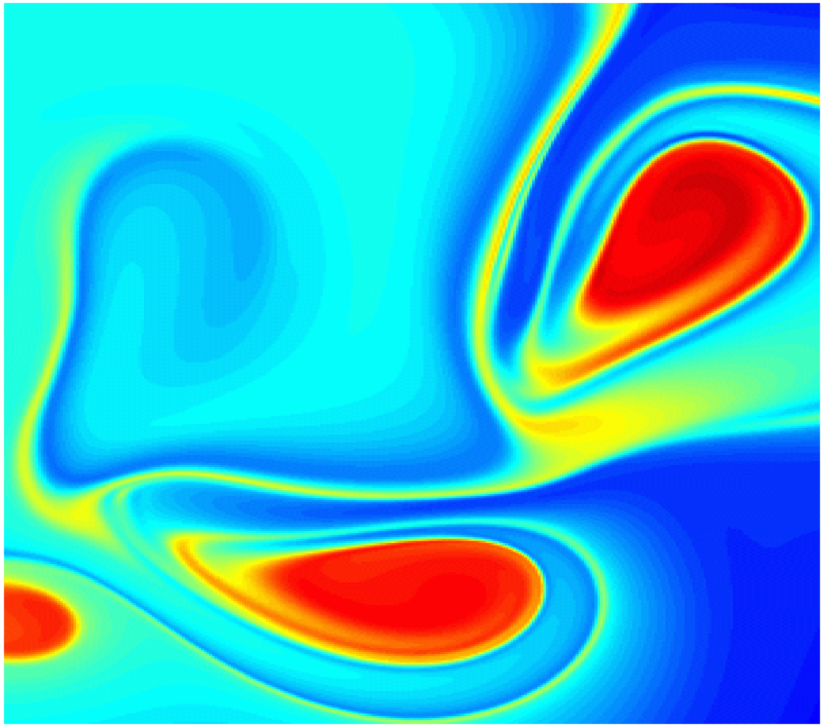


Red Storm Demonstration Run

- Polar vortex problem: Strong circumpolar jet that traps air over the poles
- Numerical Statistics
  - 13km grid spacing, 300 levels in the vertical (1 billion grid points)
  - Integrated for 288,000 time steps using 7200 CPUs for 36 hours
  - Produced 1TB of data

Polar Vortex on Red Storm





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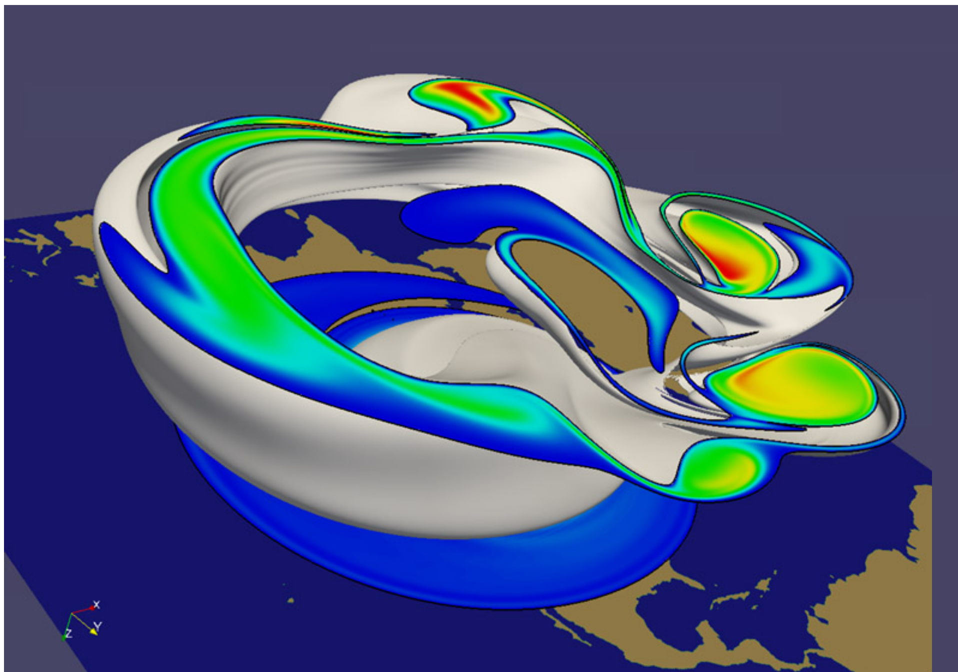
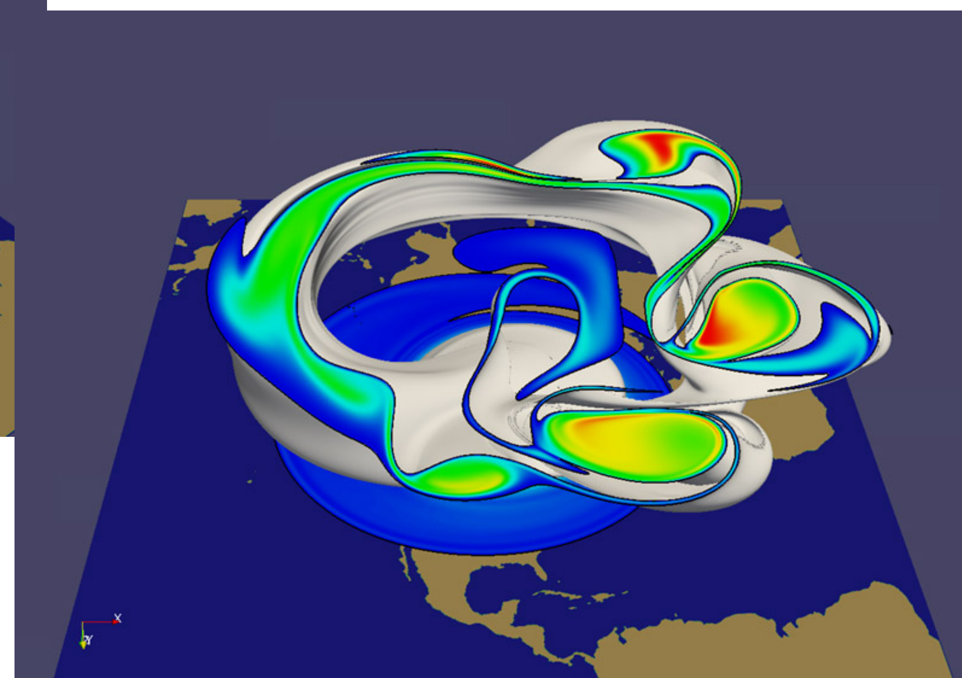
Red Storm Demonstration Run



Isosurface and contours of potential vorticity over north pole



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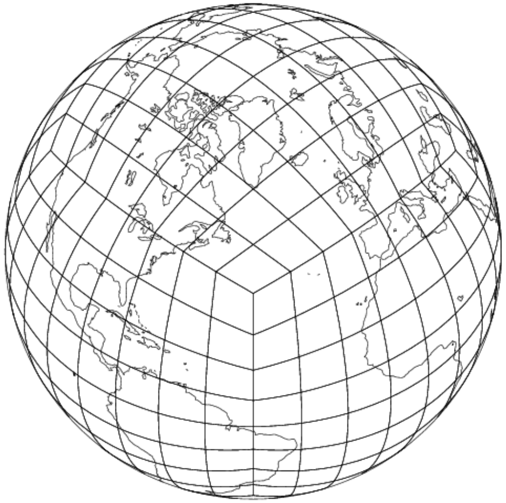
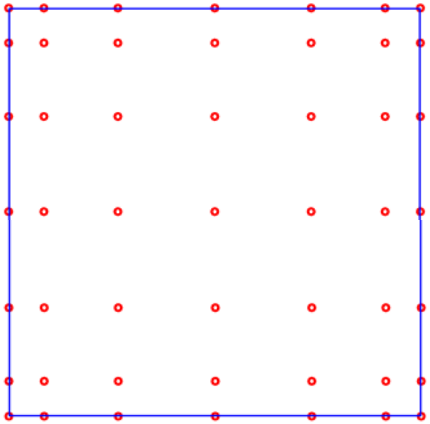
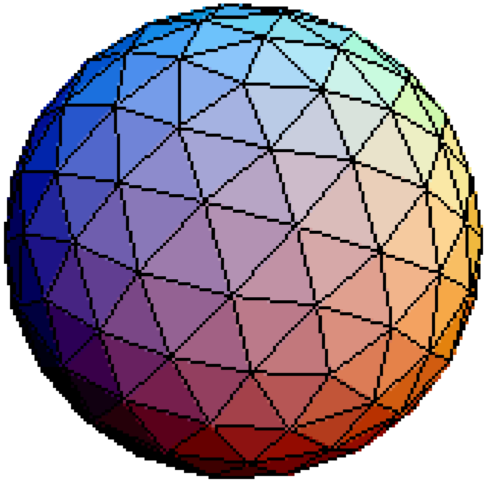
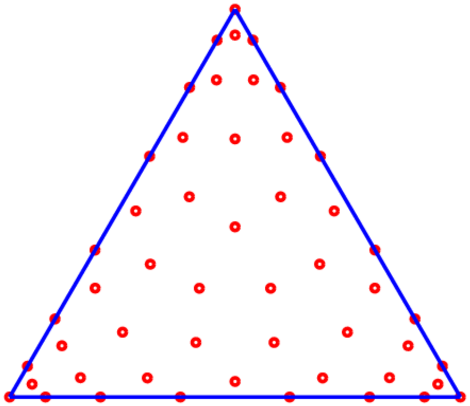
Spectral Elements in Triangles









- **Quadrilateral spectral elements**
  - **Choice of tensor-product Gauss-Lobatto points for nodal basis and quadrature leads to diagonal mass matrix and excellent interpolation properties**
- **Triangular spectral elements**
  - **Choice of nodal grid points is much more complicated . . . hard to get good interpolation and quadrature simultaneously**
- **Taylor: perform numerical optimization to look for suitable points**
- Taylor, Wingate, Bos, "A New Cardinal Function Algorithm for Computing Multivariate Quadrature Points," accepted by *SIAM J. Numer. Anal.*

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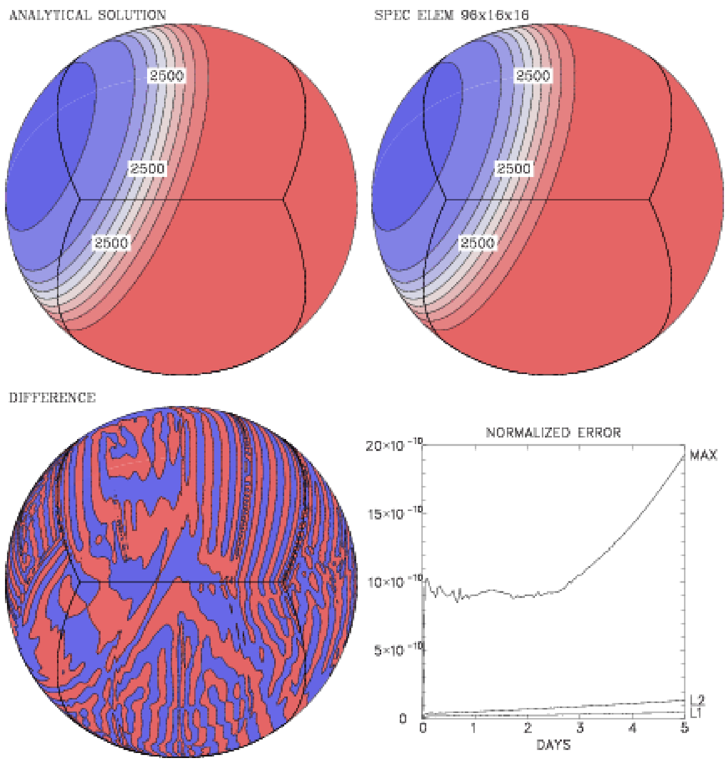
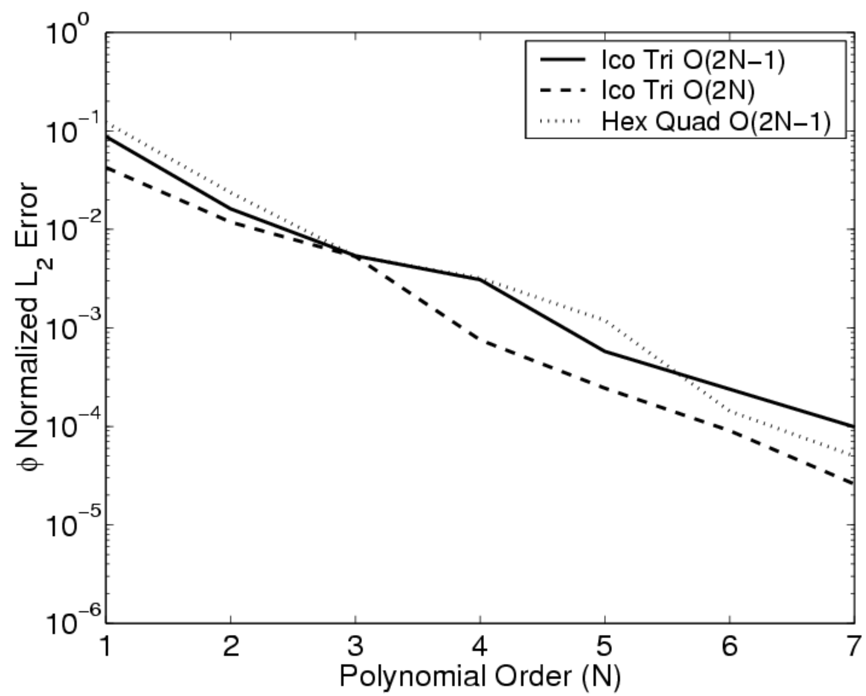
Triangular Spectral Element Results





Giraldo, Warburton, Taylor, "A Triangle-Based Spectral Element Method with Diagonal Mass Matrix," invited paper submitted to *J. Eng. Mech.* special issue on spectral interpolation and applications.