Overview of SNL 10km Climate Simulation

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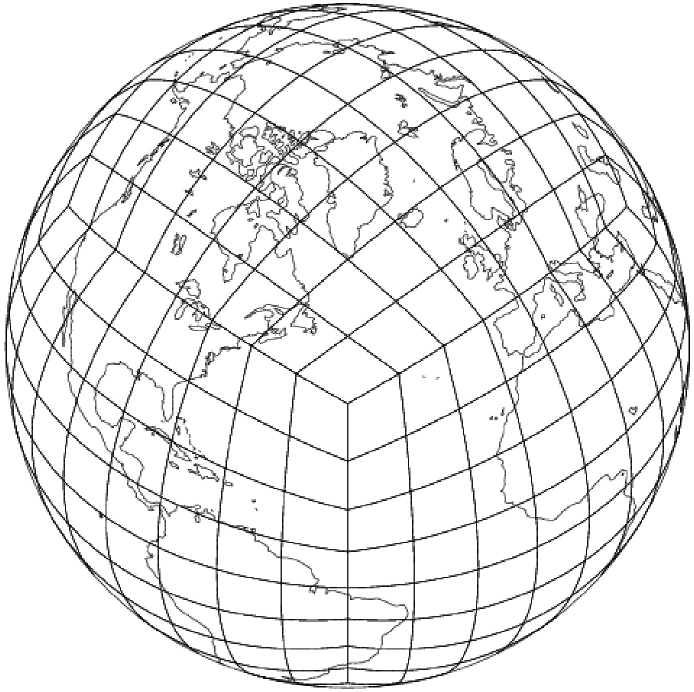
Outline

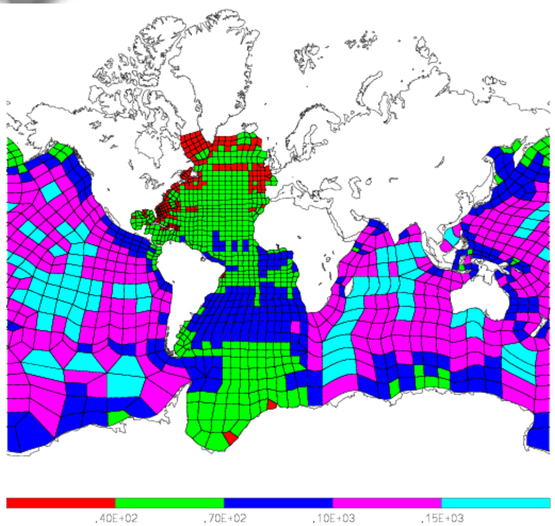
- History and status of the development of SEAM and SCD's HOMME
- Comparison of spectral elements, spherical harmonics and finite volumes
- Why 10km?
- Performance Results on Red Storm and BG/L

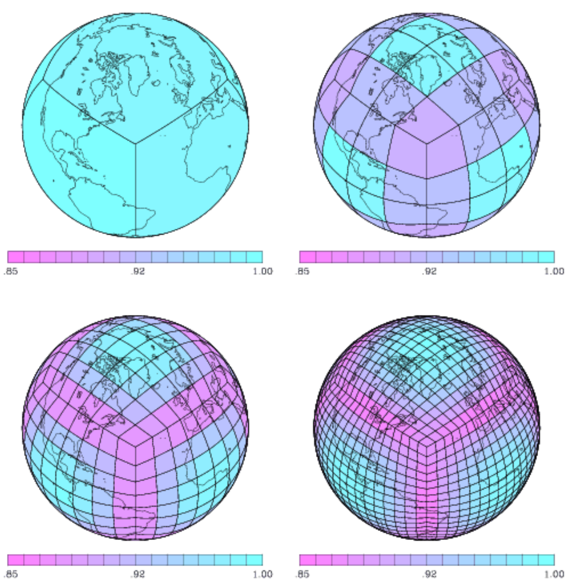
Spectral Element Atmospheric Model (SEAM)



- Spectral elements replace spherical harmonics in horizontal directions
- Coupled to the Community Atmospheric Model (CAM)
- High order (p=8) finite element method with efficient Gauss-Lobatto quadrature used to invert the mass matrix.
- Two dimensional domain decomposition: each processor contains one or more elements and the vertical columns of data associated with those elements.

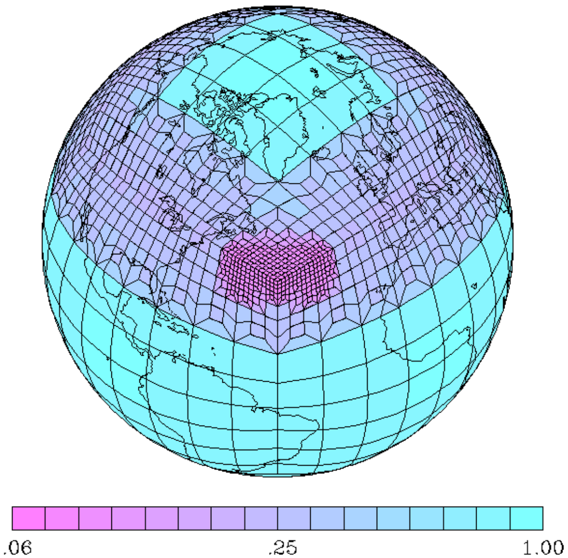
History (1/3)

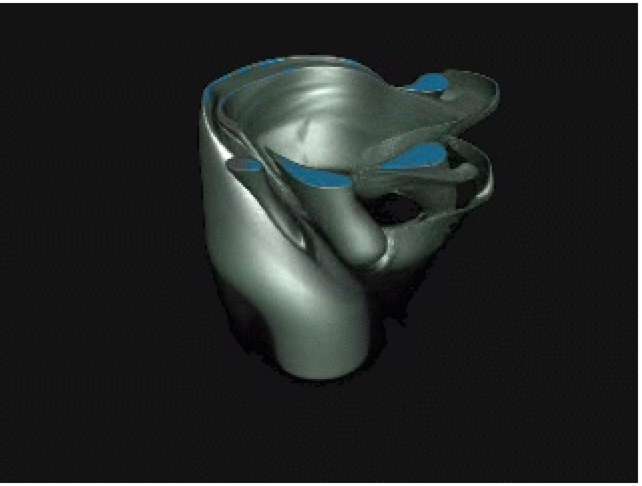




- ~1995 Haidvogel, Iskandarani: SEOM
- 1997, Taylor, Tribbia, Iskandarni, *The spectral element method for the shallow water equations on the sphere*, JCP
- 1998, Taylor, Loft, Tribbia, *Performance of a spectral element atmospheric model (SEAM) on the HP Exemplar SPP2000*, NCAR TN-439+EDD
- 2002, Thomas, Loft, *Semi-implicit spectral element atmosphere model*, J. Sci. Comput.
- 2003, Spotz, Sandia CSRF Award to collaborate w/NCAR
- 2004, Fournier, Taylor, Tribbia, *The Spectral Element Atmosphere Model (SEAM): High-resolution parallel computation and localized resolution of regional dynamics*, MWR
- 2004, Spotz, Sandia LDRD Award to collaborate w/NCAR

History (2/3)





- 2005, Thomas, Loft, *The NCAR spectral element climate dynamical core: Semi-implicit Eulerian formulation, J. Sci. Comput.*
- 2005, Dennis, Fournier, Spotz, St.-Cyr, Taylor, Thomas, Tufo, *High Resolution Mesh Convergence Properties and Parallel Efficiency of a Spectral Element Atmospheric Dynamical Core*, IJHPCA.
- 2005, Nair, Thomas, Loft, *A Discontinuous Galerkin Transport Scheme on the Cubed-Sphere*, MWR (in review)
- 2005, St-Cyr, Thomas, *Nonlinear Operator Integration Factor Spliting for the Shallow Water Equations*, Appl. Num. Math.
- 2005, St-Cyr, Dennis, Thomas, Tufo, *An adaptive nonconforming spectral element atmospheric model,* J. Sci. Comput. (in review)

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History (3/3)

- **NCAR/UMD:** Baer, Tribbia, Wang: AMIP runs in CAM (Semi-Lagrange for moisture transport)
- **NCAR/CSU:** Nair, Rasch, Tufo : DG for moisture transport
- **SANDIA:** Spotz, Taylor : Spherical Harmonics “drop in replacement” in CAM: Aqua planet
- **NCAR***:* Loft, Thomas: Aqua planet with Emmanuel Cumulous Parametrization
- **NCAR:** St-Cyr, Thomas: AMR for the primitive equations

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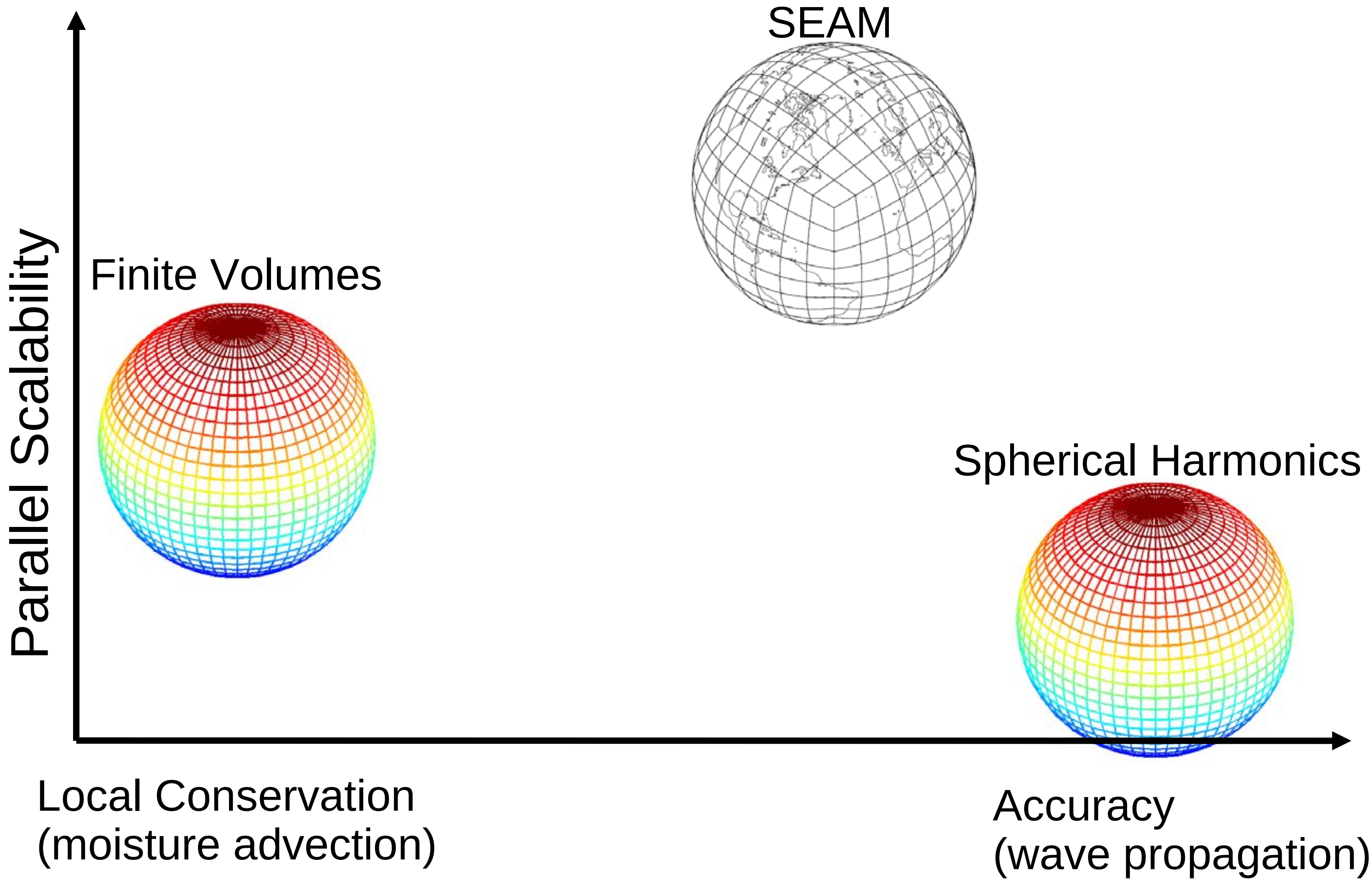
Atmospheric Dynamical Cores



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?)

Goal: Demonstrate Global 10km capability on MPPs

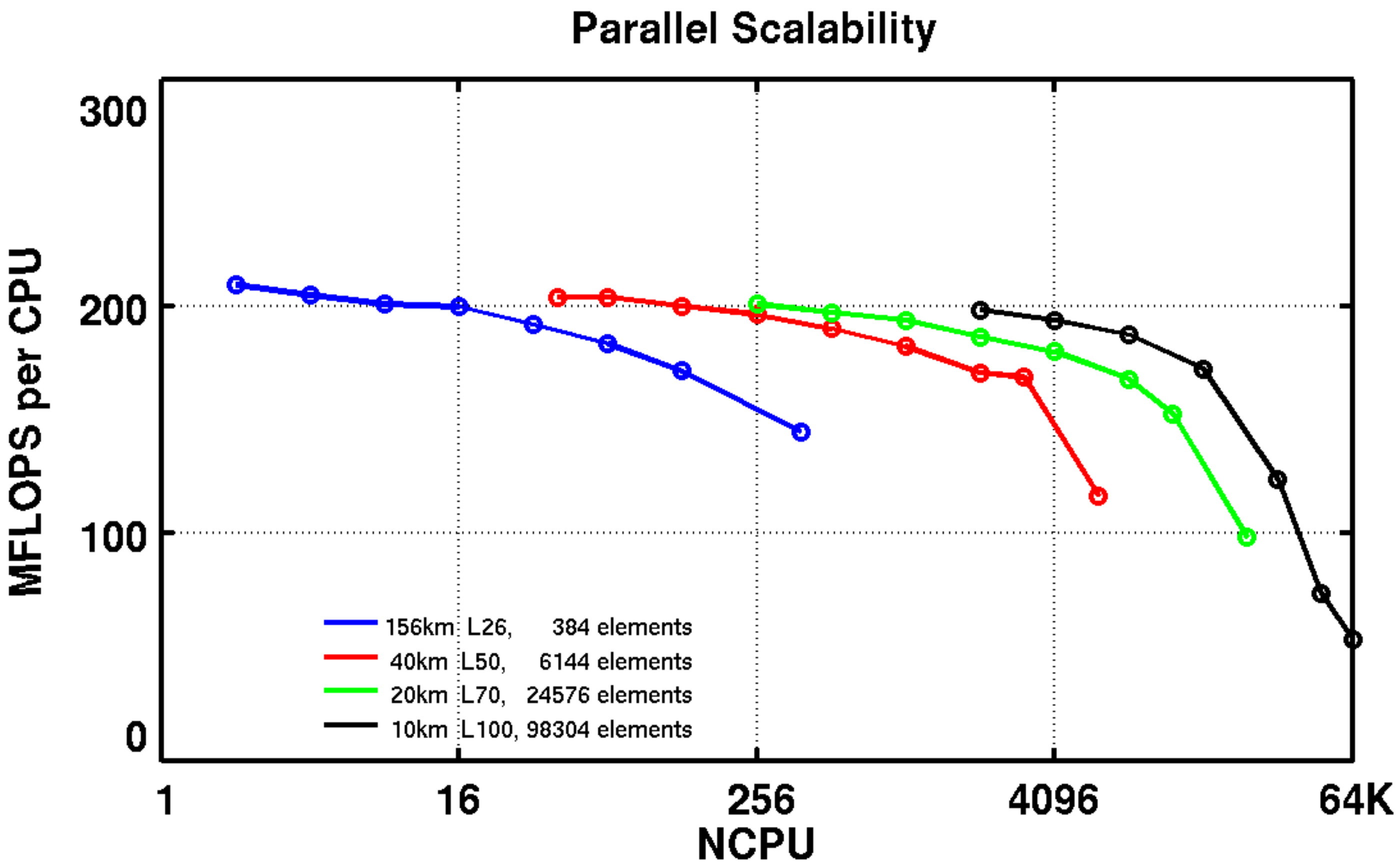
- DOE SCaLeS Report
  - "An important long-term objective of climate modeling is to have the spatial resolution of the atmospheric and oceanic components both at ~1/10° (~ 10 km resolution at the Equator)."
- Atmospheric Model
  - At 10km, the atmosphere will be the dominant component of a coupled model.
  - 10km is necessary to resolve regional detail of temperature and precipitation important for local and social impacts of climate change
  - 10km dynamics for improved tracer advection, with physics at lower resolution
  - Many forecast models use 10km regional resolution and hydrostatic equations: could replace with a single global forecast model.

Global 10km + AMR

Proven global 10km capability plus AMR capability implies:

- Global model (150km) with selected 10km regional resolution
- Requires only moderate computing resources
- Full, two-way interaction
- Avoid nesting
- Research issues for coupling 150km and 10km physics

SEAM on BG/L



Max: 4TF

Performance of 4 fixed problem sizes, on up to 64K CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.

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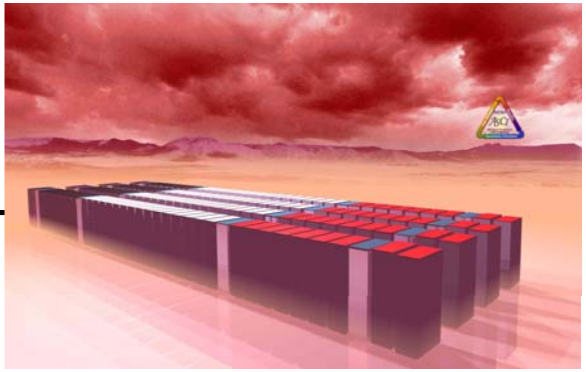
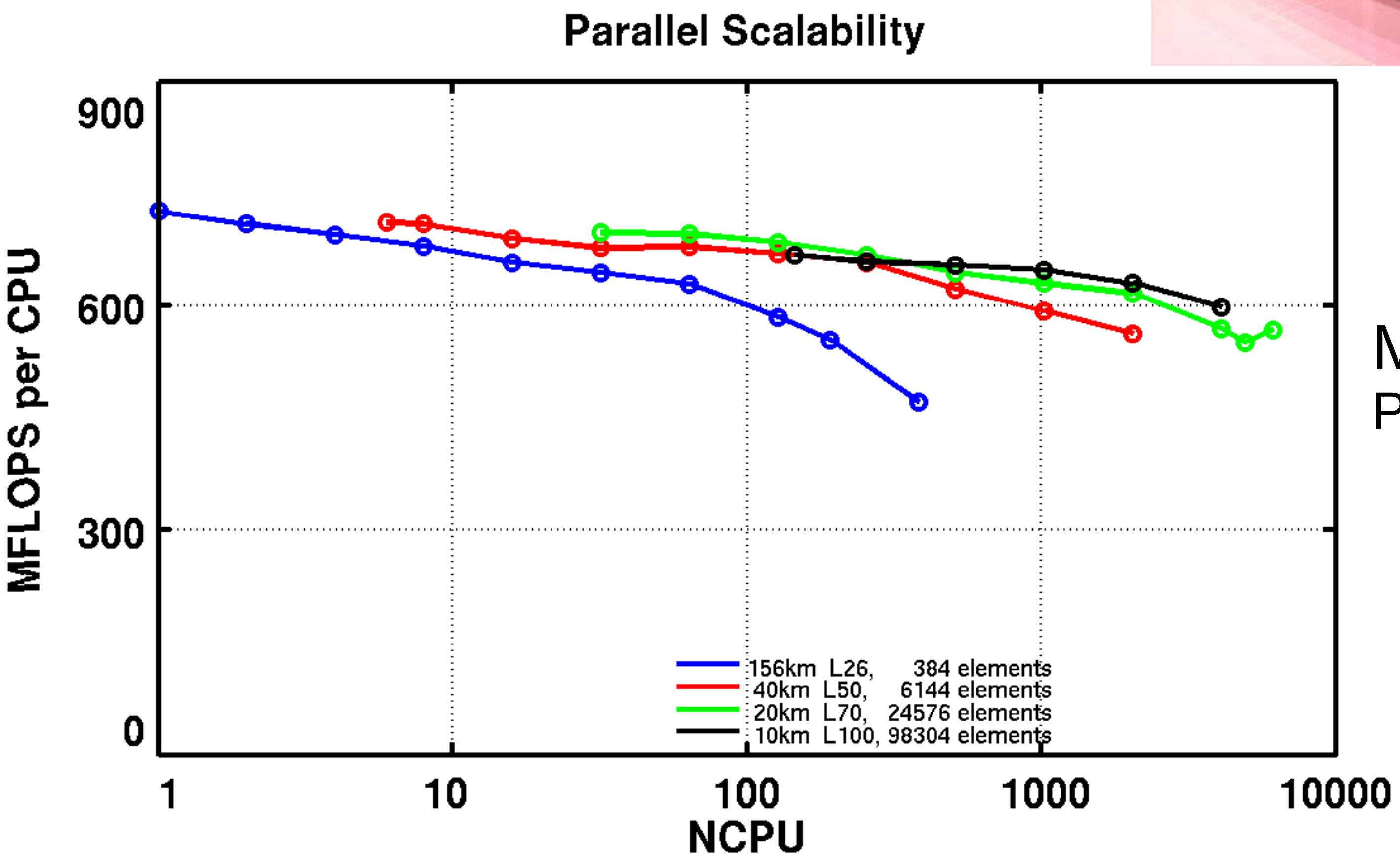
SEAM on Red Storm





Max: 4TF
Projected: 6TF

Performance of 4 fixed problem sizes, on up to 6K CPUs. The annotation gives the mean grid spacing at the equator (in km) and the number of vertical levels used for each problem.

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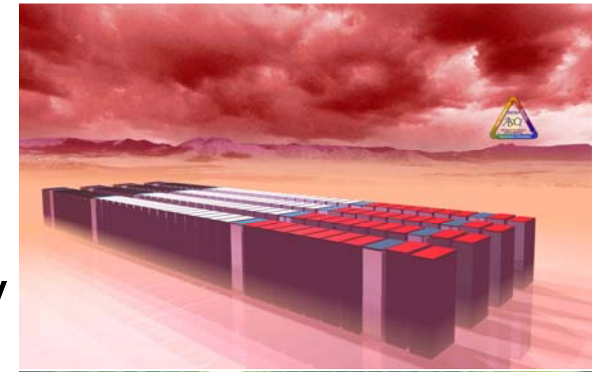
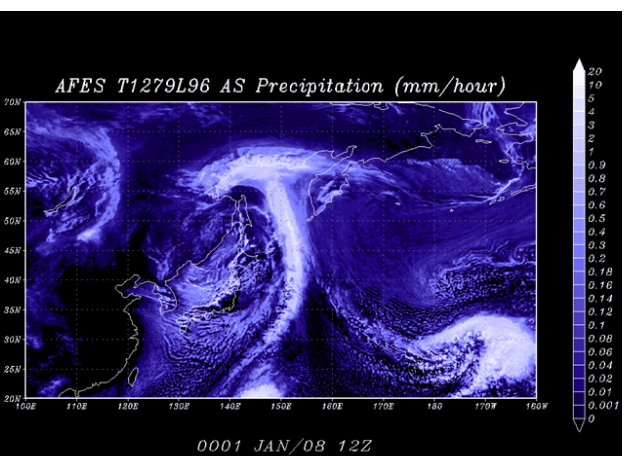
Integration Rates

- SEAM on Red Storm & Blue Gene/L
  - Aquaplanet
  - 40 km (3 TF) 7-30 simulated years per day
  - 10 km (6 TF) 25-100 simulated days per day
- AFES on Earth Simulator
  - Global Spectral Model (spherical harmonics)
  - Full physics
  - 10km (24TF) 57 simulated days per day





Conclusions

- Current Results
  - 10km on MPP
  - AMR for shallow water
- Current efforts
  - Aquaplanet
  - AMIP
  - 3D AMR
- Future research (SACC)
  - Physics with AMR
  - Additional validation

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

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

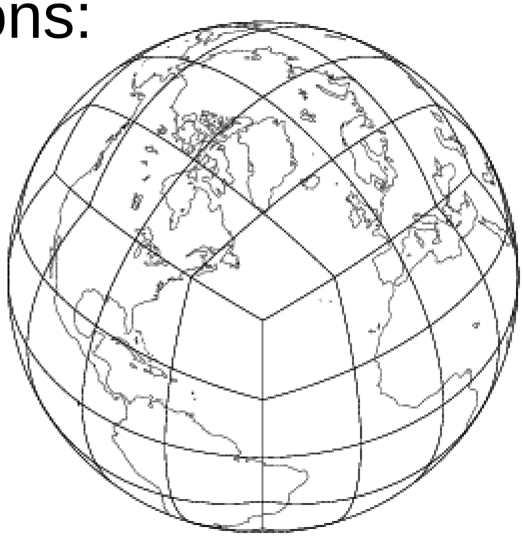
$$\frac{\partial h}{\partial t} + \nabla \cdot (h\mathbf{u}) = 0$$

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

Shallow Water Equations Integral Formulation

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

Decompose domain *D* into rectangular regions:



$$\sum_D \int \frac{\partial h}{\partial t}\phi dA = -\sum_D \int \nabla \cdot (h\mathbf{u})\phi dA$$

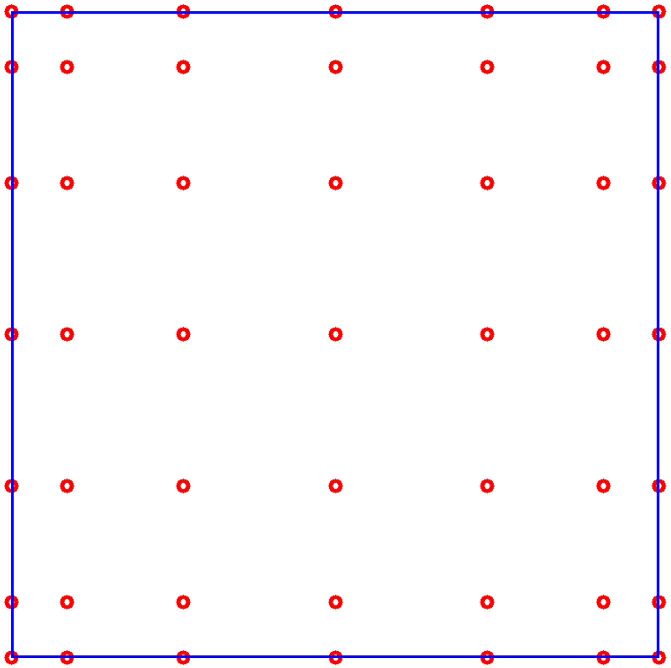
Spectral Element Discretization

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

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

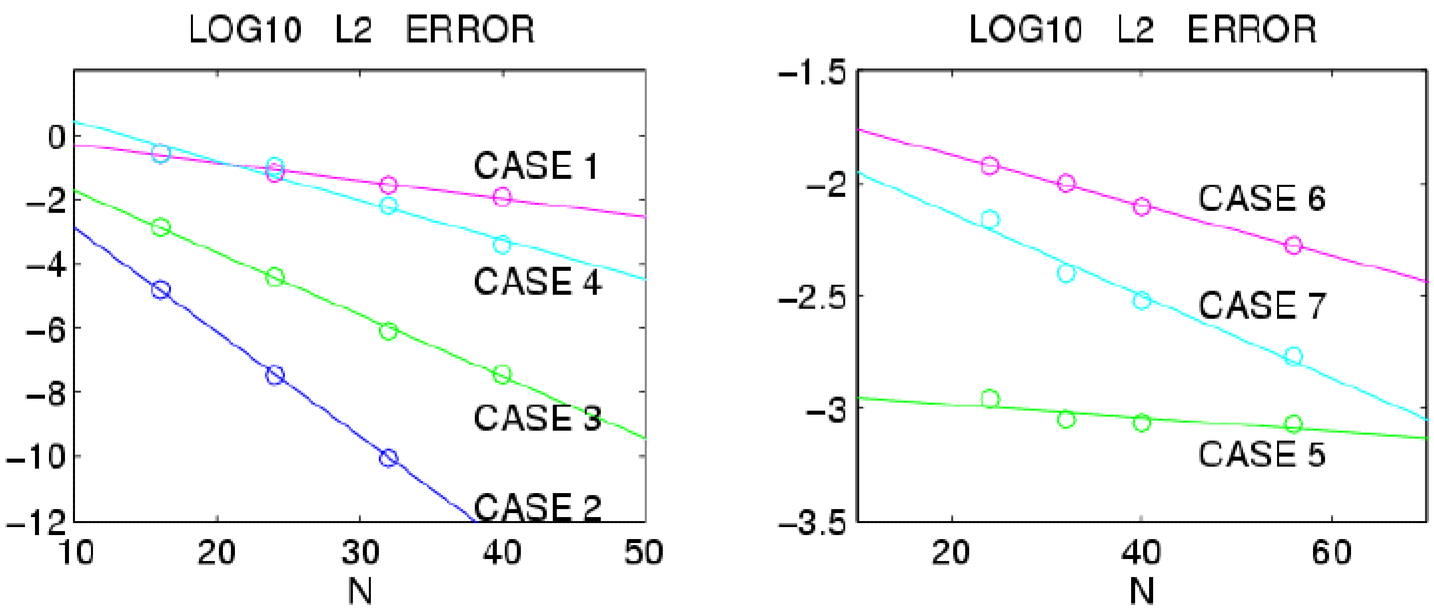
  $\{w_i\}$ = associated Newton-Cotes weights

$$\int \frac{\partial h}{\partial t}\phi\, dA \approx \sum_i w_i \frac{\partial h}{\partial t}(z_i)\phi(z_i)$$



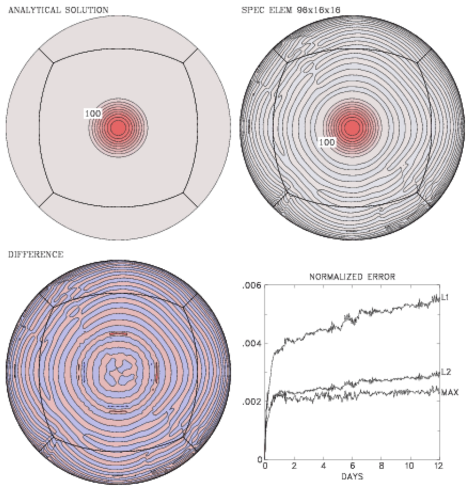
Shallow Water Equations on the Sphere

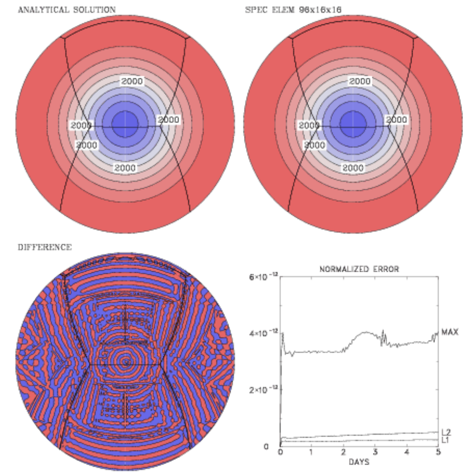
p refinement with 6 elements

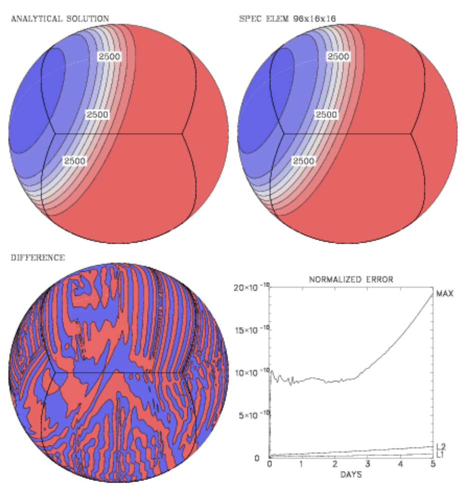


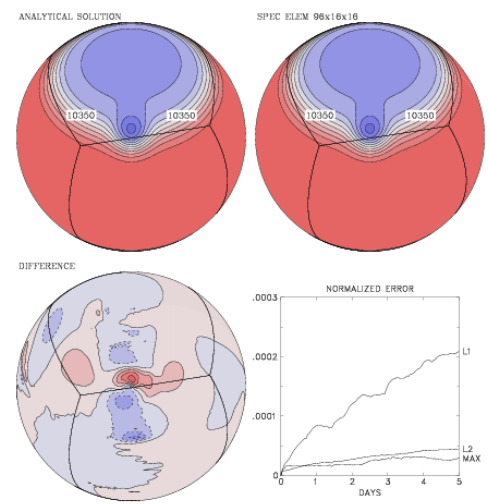
Williamson, Drake, Hack, Jakob, Swarztrauber, *A standard test set for the numerical approximations to the shallow water equations in spherical geometry*, J. Comput. Phys., 1992.
Taylor, Tribbia, Iskandarani, J. Comput. Phys., 1997

Shallow Water Equations on the Sphere









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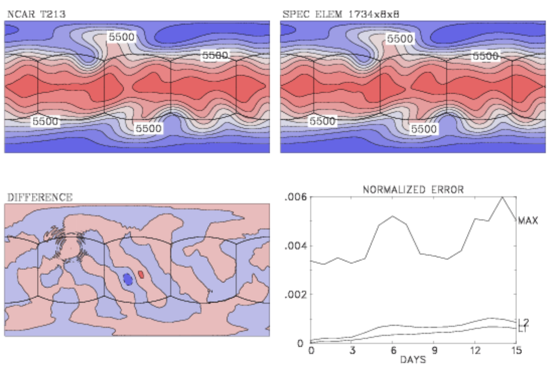
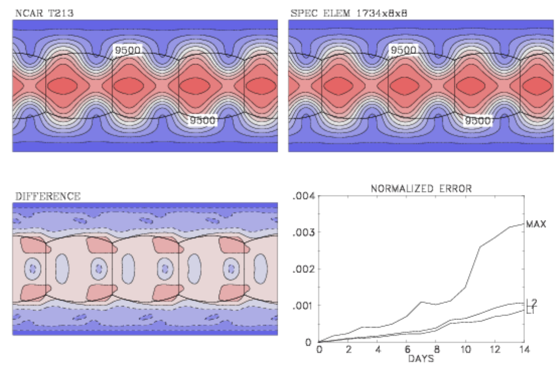
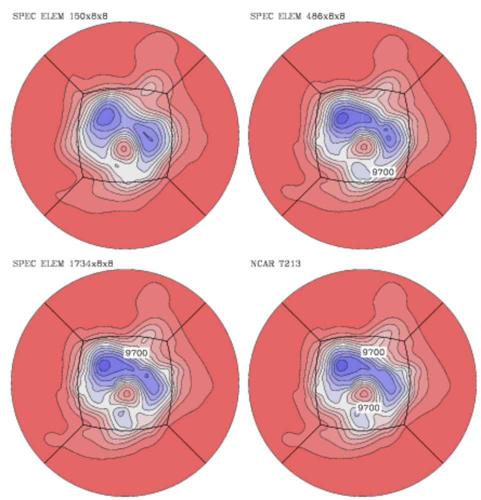
Shallow Water Equations on the Sphere







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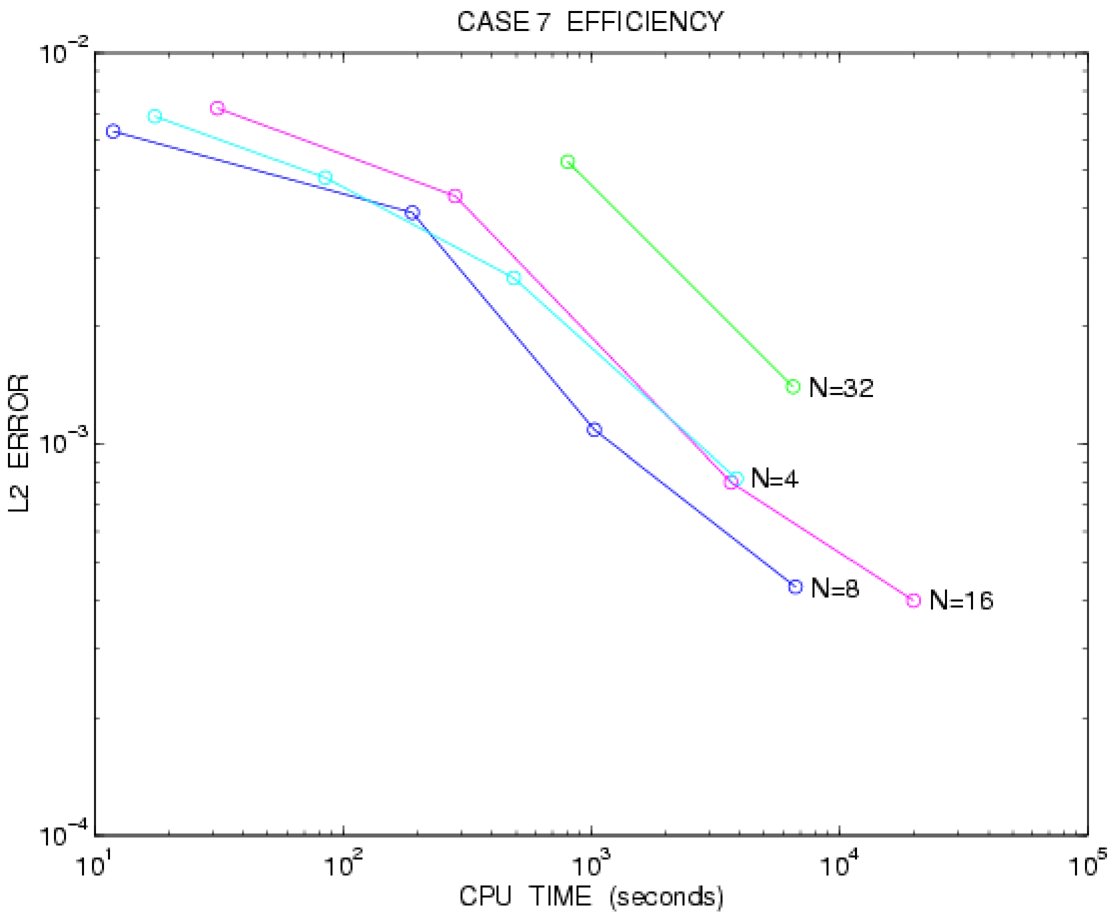
Shallow Water Equations on the Sphere

Test 7:   p vs. h refinement



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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.