MCore: A High-Order Accurate Finite-Volume Dynamical Core

Paul Ullrich

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Dynamical Core Model Intercomparison Project (DCMIP) 2012 Summer School

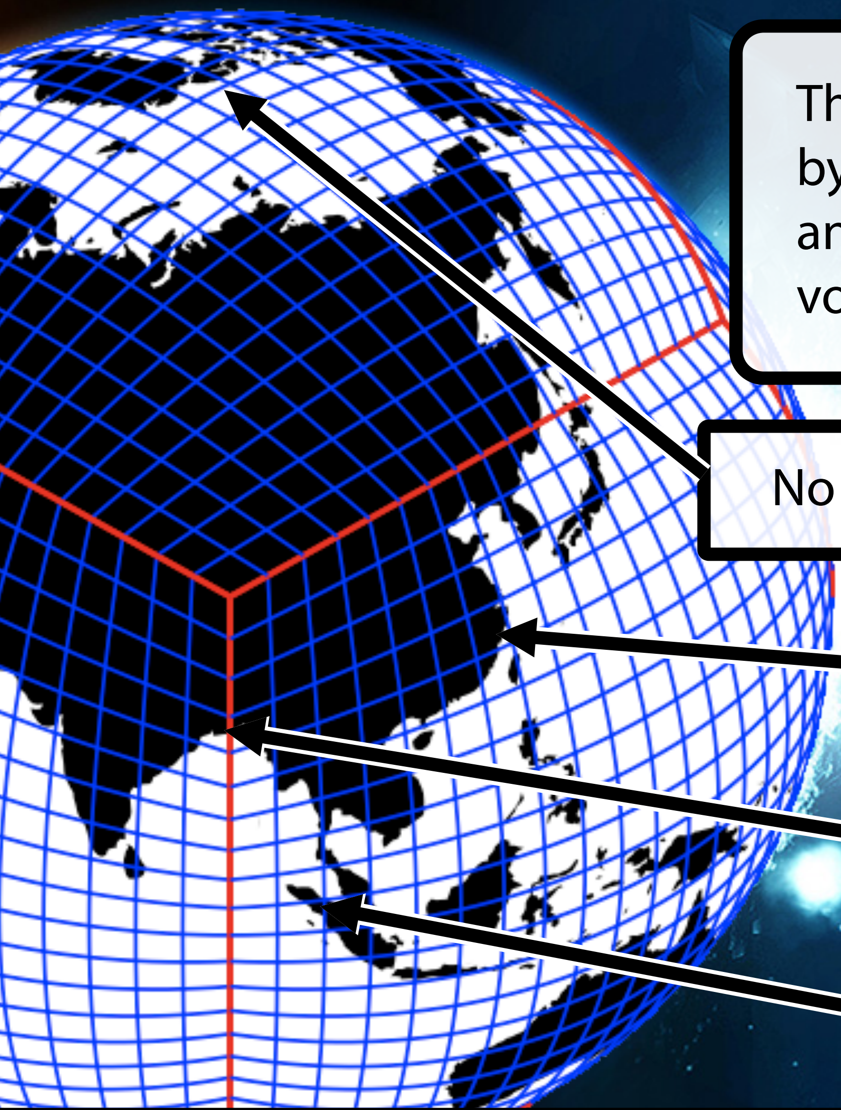
DCMIP

Mission Statement / Goal

Our goal is to develop a ***non-hydrostatic*** and ***multi-resolution*** modeling environment which is ***high-order accurate***, ***scalable*** on parallel hardware and ***effective*** for modeling regional and global scales.

The Cubed-Sphere

The cubed-sphere grid is obtained by placing a cube inside a sphere and "inflating" it to occupy the total volume of the sphere.



No polar singularities

Grid faces individually regular

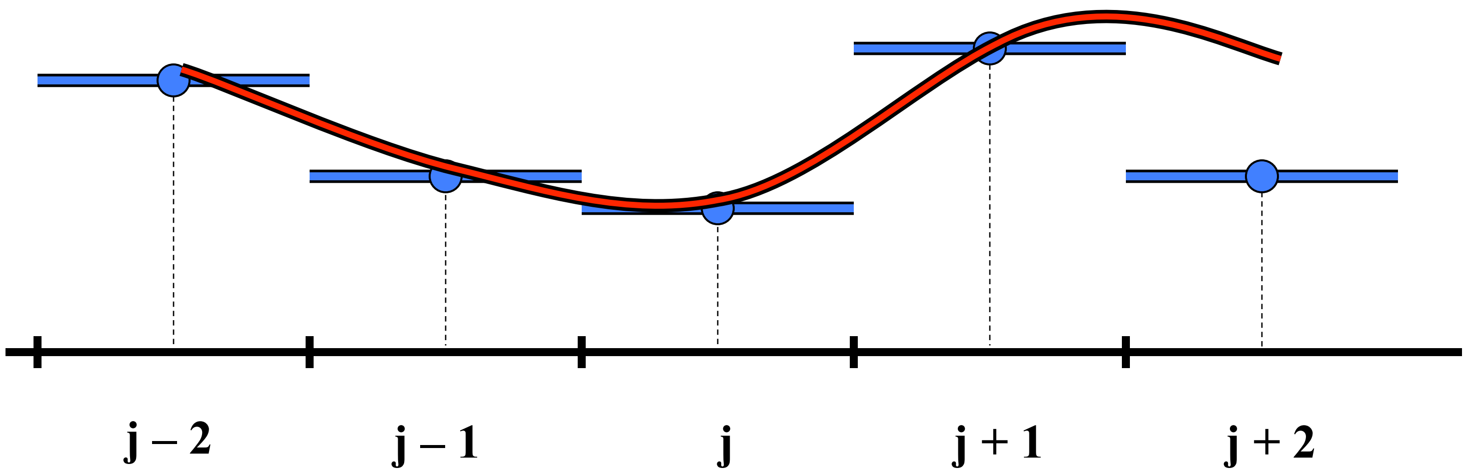
Some difficulty at panel edges

Non-orthogonal coordinate lines

Finite-Volume Methods

- State variables (density, momentum, energy) are stored as element-averaged values (conservation)
- Finite-volume methods do not suffer from "spectral ringing" and generally only realize physically attainable states (easy to apply diffusion locally)
- Finite-volume methods can be easily made to satisfy monotonicity and positivity constraints (i.e. to avoid negative tracer densities)
- High-order techniques can reduce grid-imprinting due to the cubed-sphere geometry

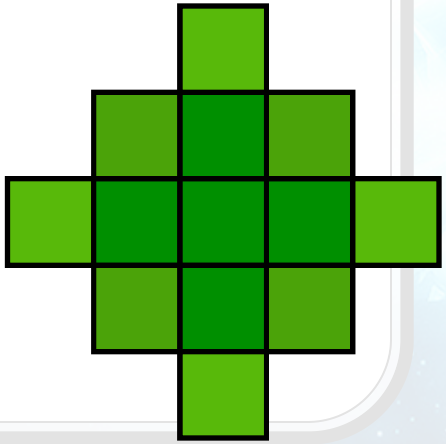
Sub-Grid Scale Reconstruction



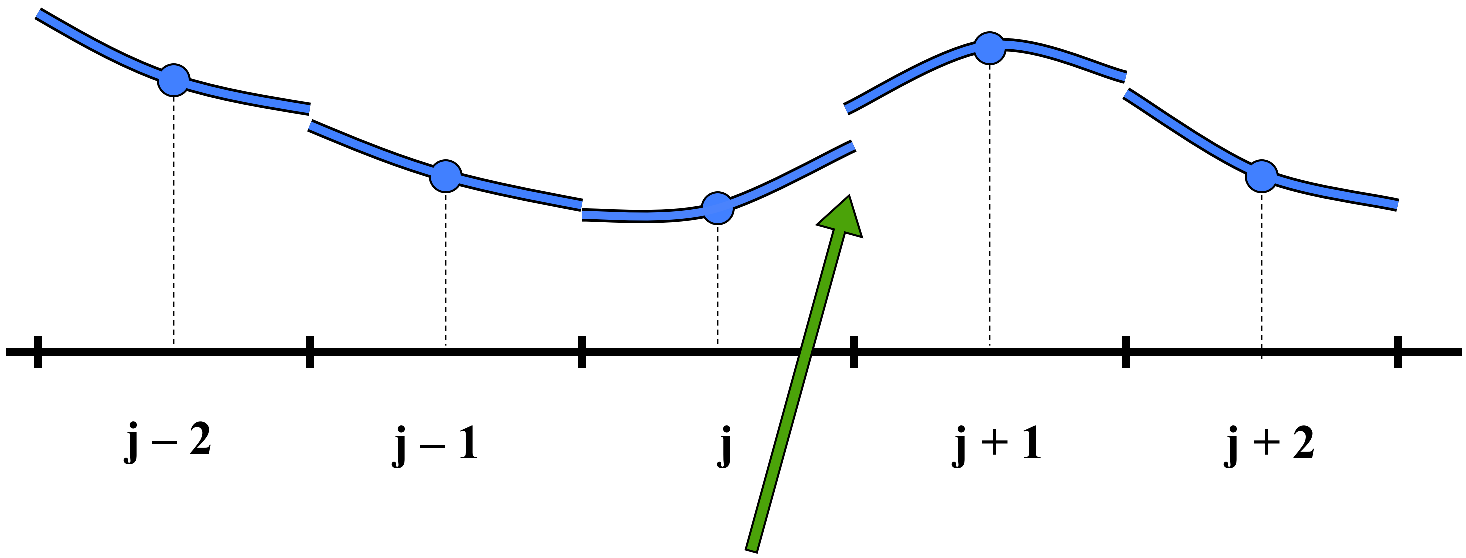
A reconstructed cubic polynomial through an element and its four nearest neighbors provides fourth-order sub-grid accuracy.

2D Stencil

A "diamond"-shaped 5x5 stencil yields fourth-order accuracy without dimension splitting.

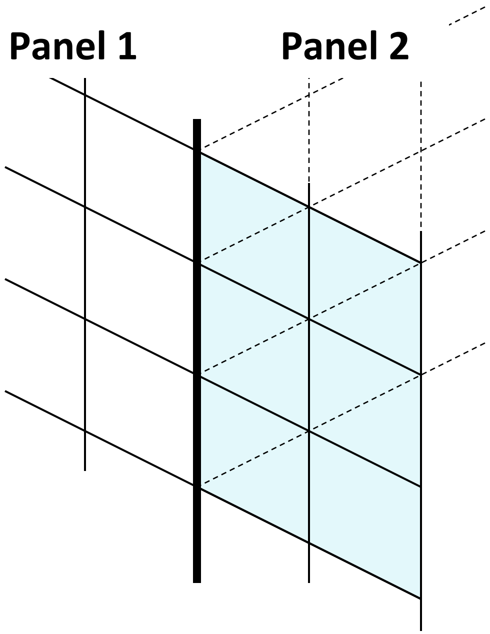


Sub-Grid Scale Reconstruction

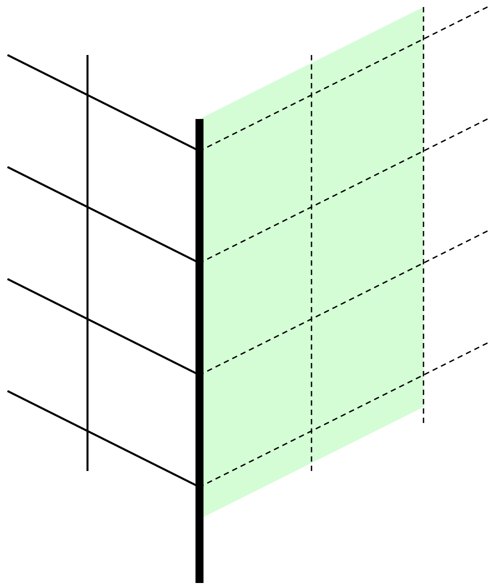


Discontinuities are preserved at element boundaries. These will allow us to gauge the "roughness" of the distribution and target numerical diffusion accordingly.

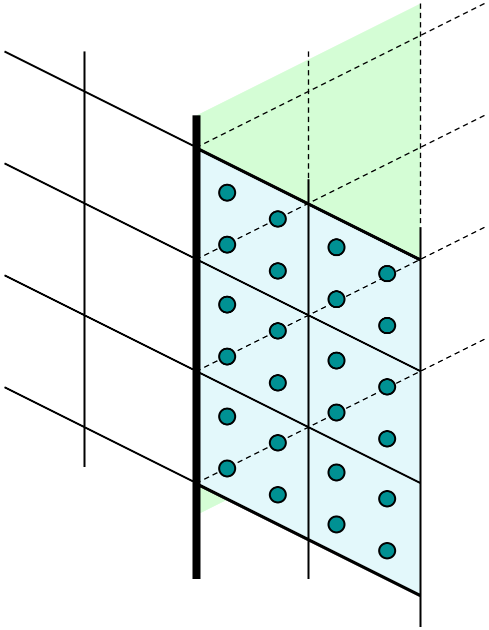
MCore: Treatment of Panel Edges



Cell-averaged quantities are required in the blue shaded area.

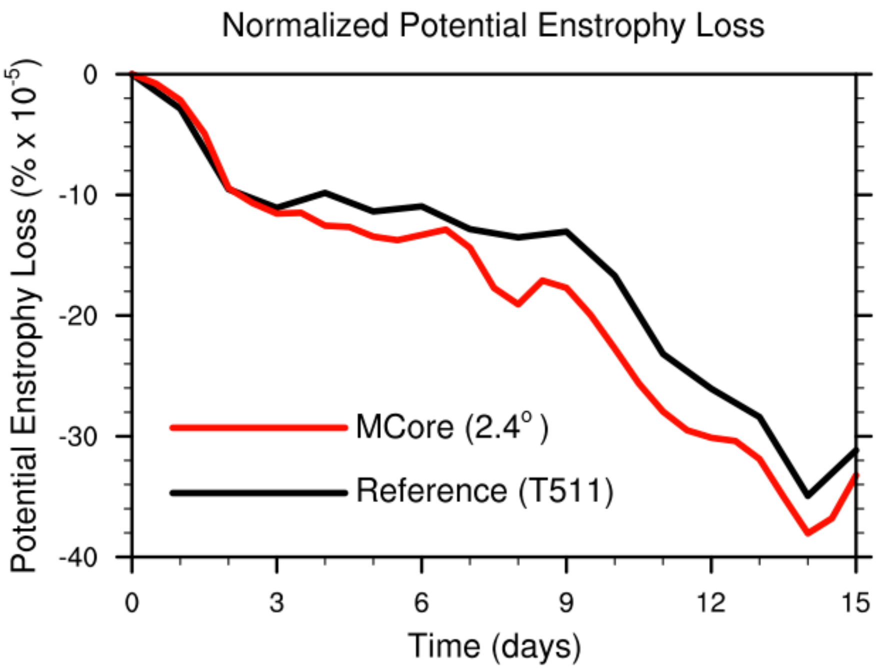


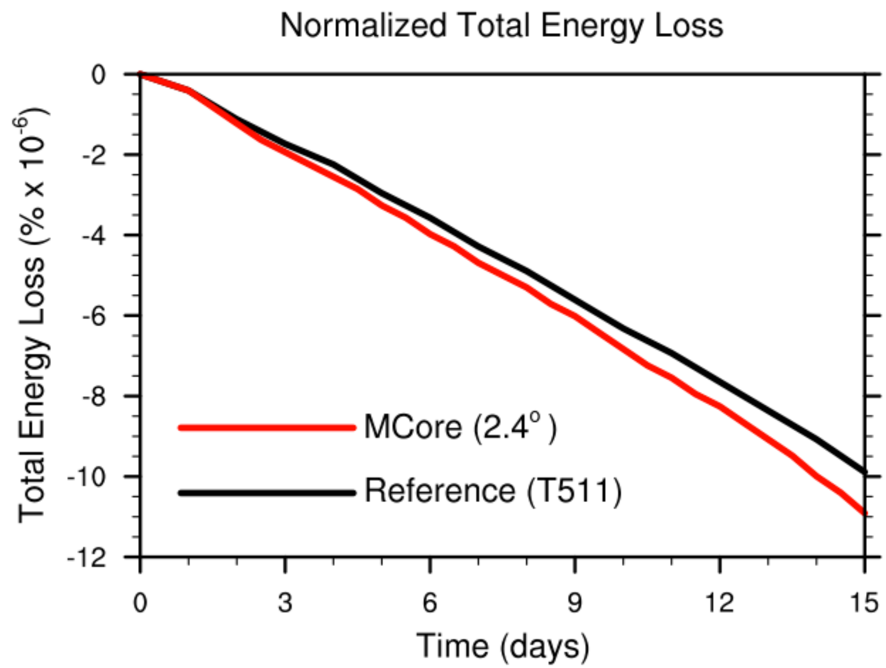
Step 1: Use one-sided stencils to reconstruct information in green shaded area.



Step 2: Sample one-sided reconstruction at Gaussian quadrature points to obtain cell-averaged value

Shallow-Water Flow over Topography



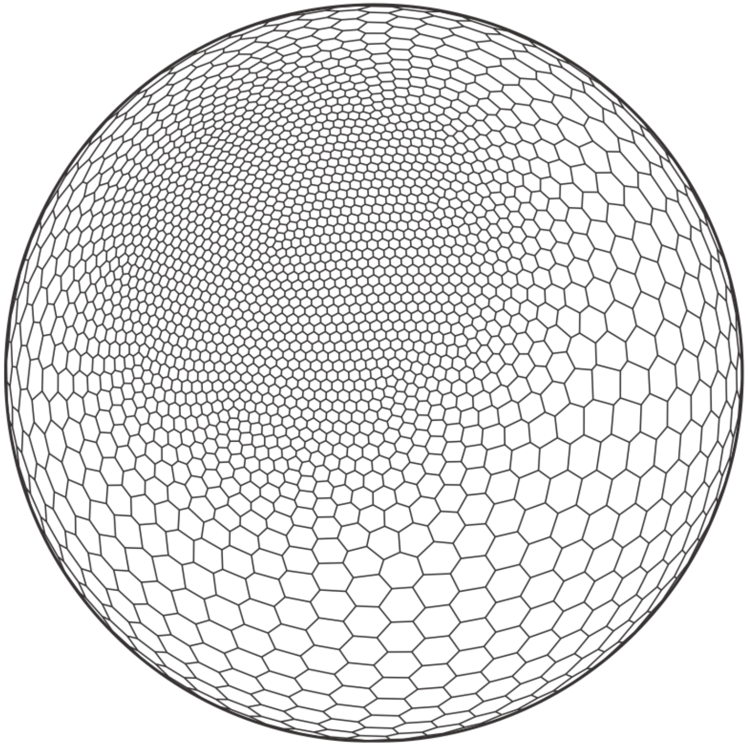


Reference solution from high-res STSWM solution remapped to c40 grid.

Total energy loss comparable to CAM-SE with largest time step.

Source: Ullrich, Jablonowski and van Leer (2010) "Finite-volume methods for the shallow-water equations on the sphere." J. Comp. Phys.

Designing a Multi-Resolution Model

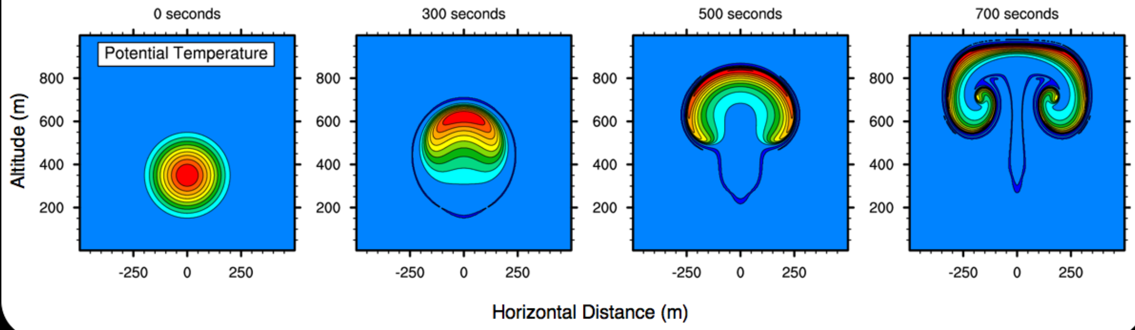


Model for Prediction Across Scales (MPAS) Stretched Grid

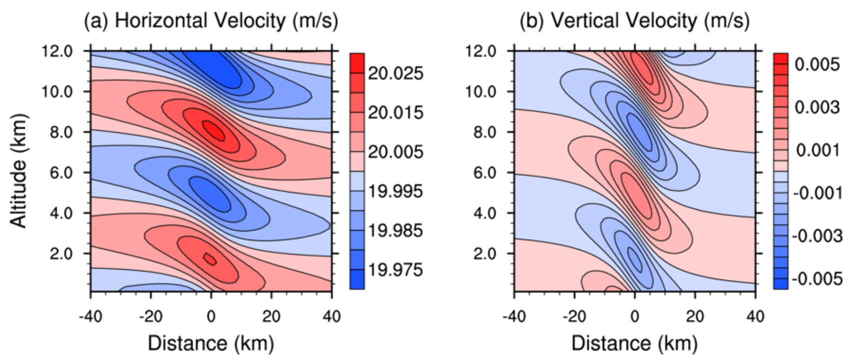
MCore / Chombo Non-conformal Grid

Cartesian Geometry Results

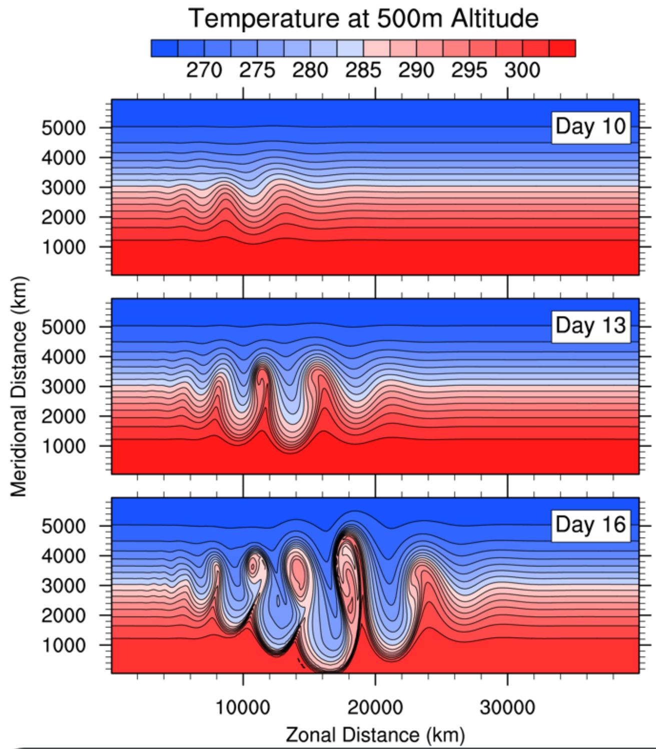
Rising Thermal Bubble
Microscale



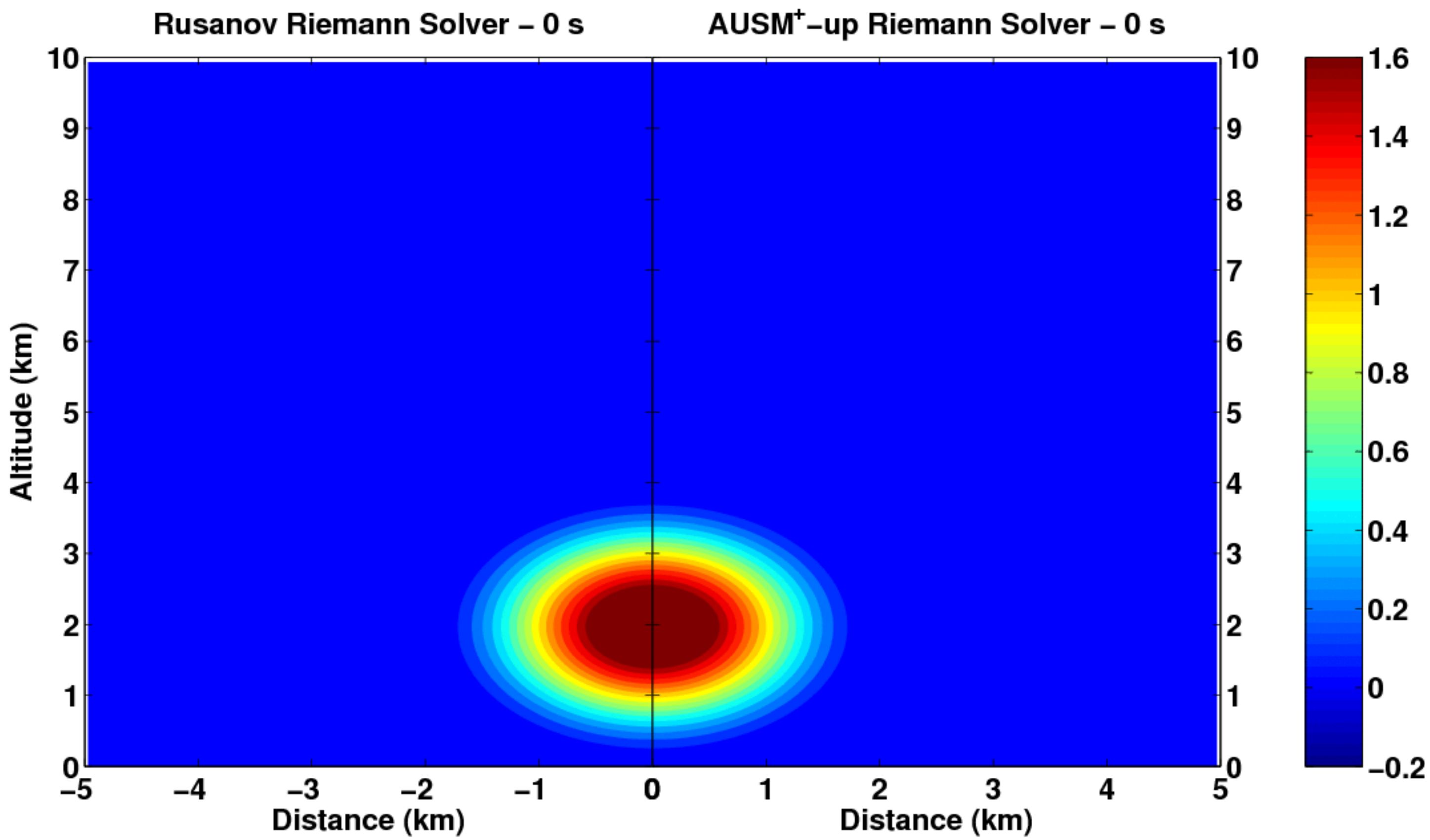
Hydrostatic Mountain Waves
Mesoscale



Breaking Baroclinic Waves
Global scale

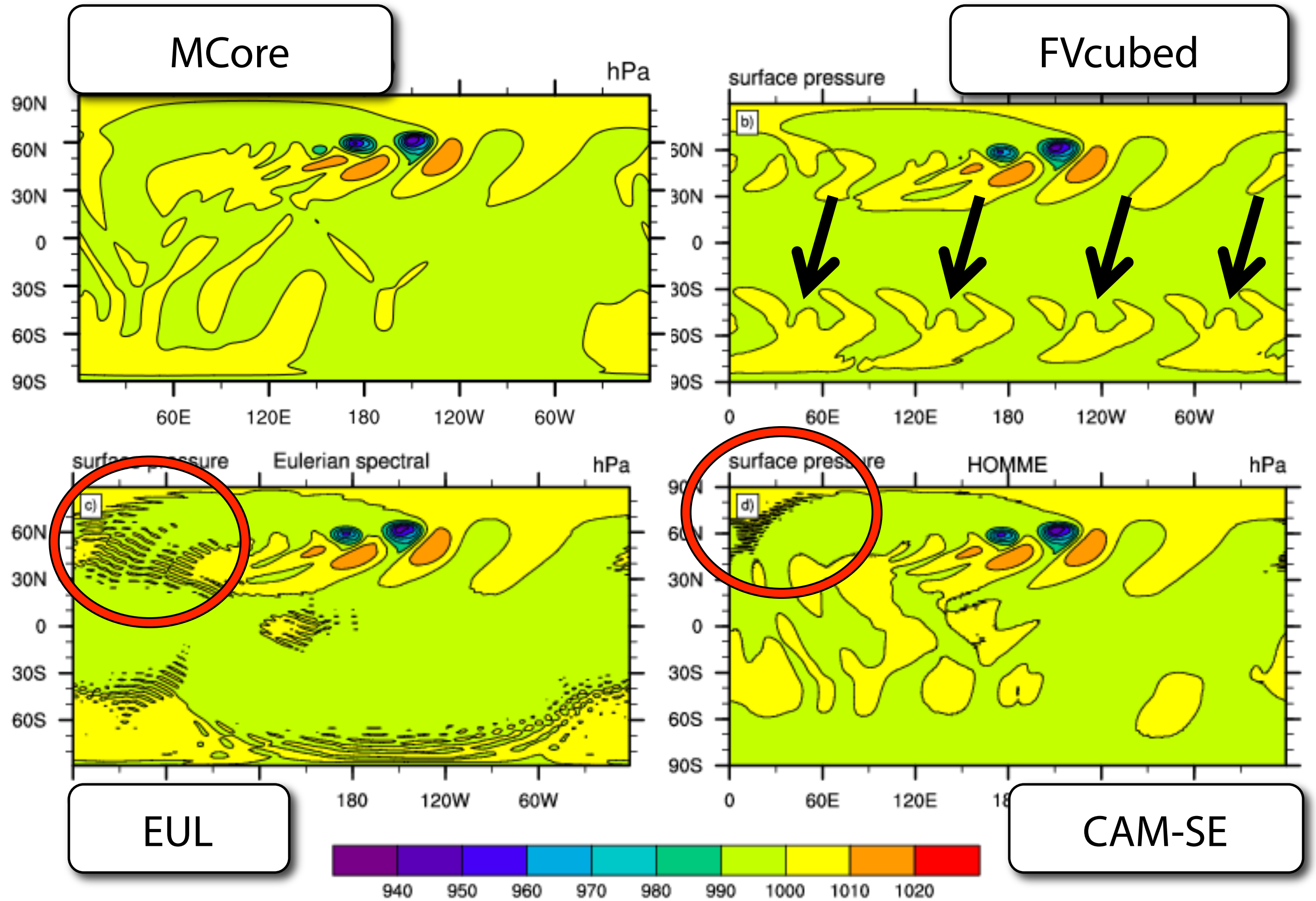


Breaking baroclinic waves in a large Cartesian channel with constant Coriolis force.

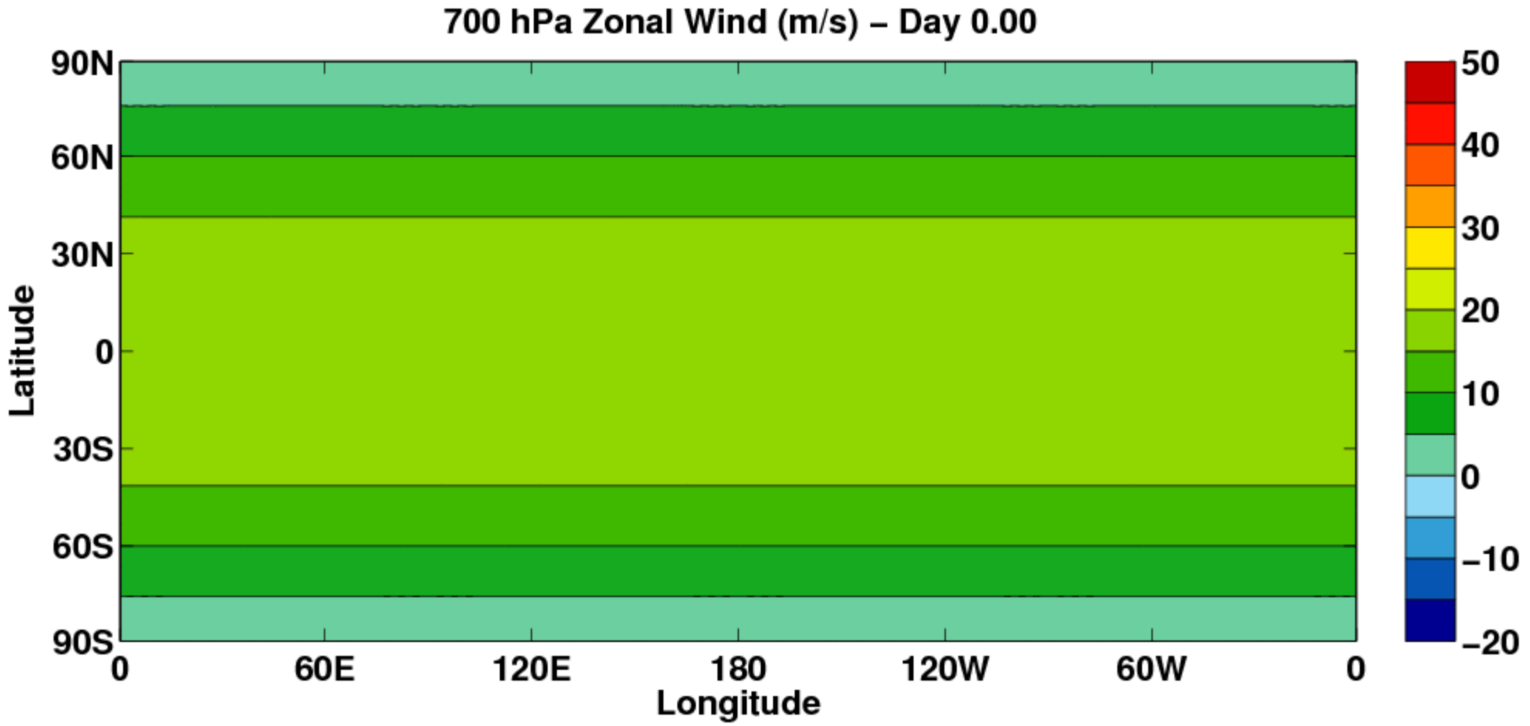


A simulated rising thermal bubble using the Rusanov flux (left) and AUSM+-up flux (right) and high-order finite-volume reconstruction. Potential temperature perturbation shown.

Baroclinic Instability on the Sphere

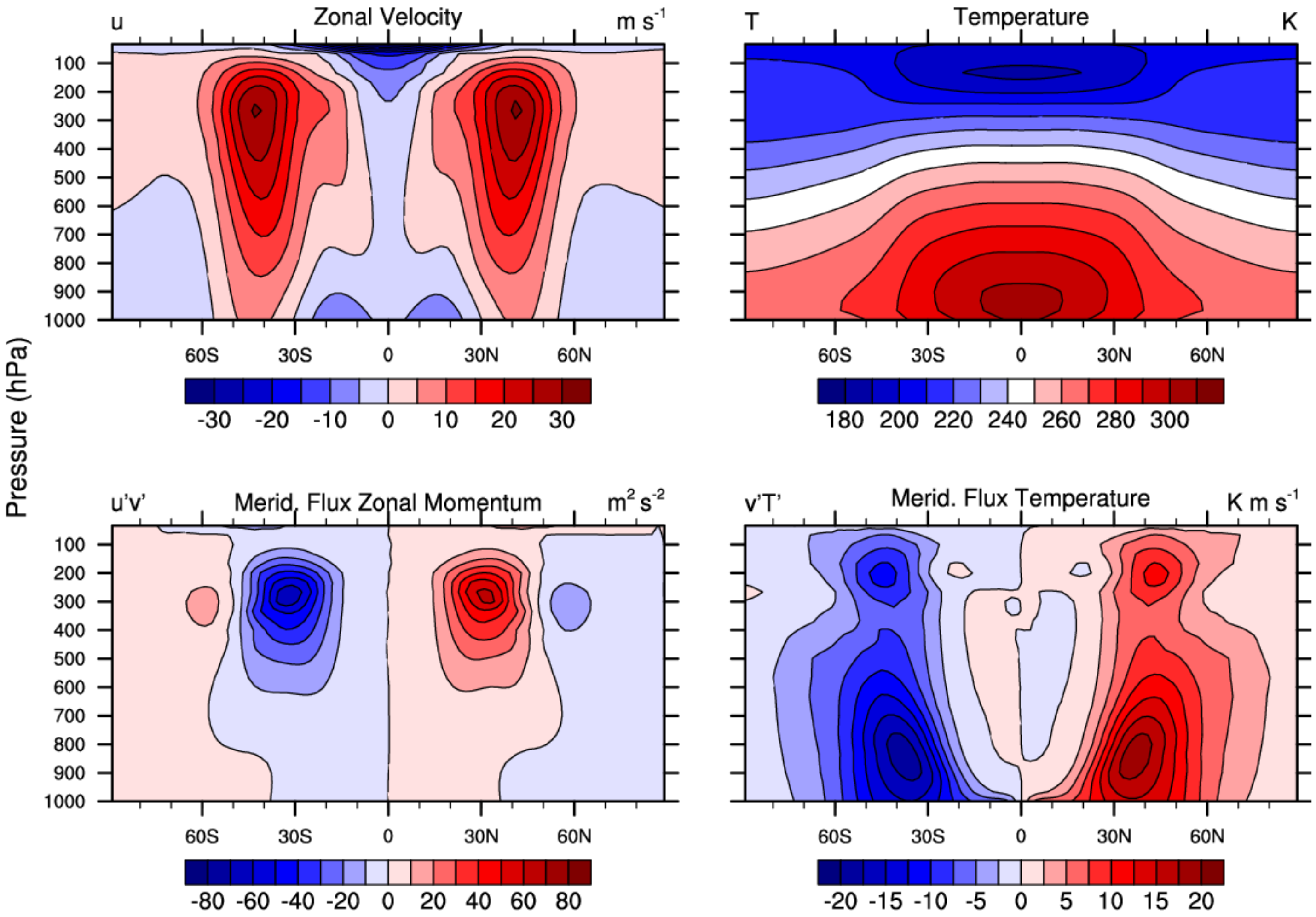


Flow Over Topography (3D)



Source: Ullrich and Jablonowski (2011) "MCore: A non-hydrostatic atmospheric dynamical core utilizing finite-volume methods." Under revision.

Held-Suarez Climatology

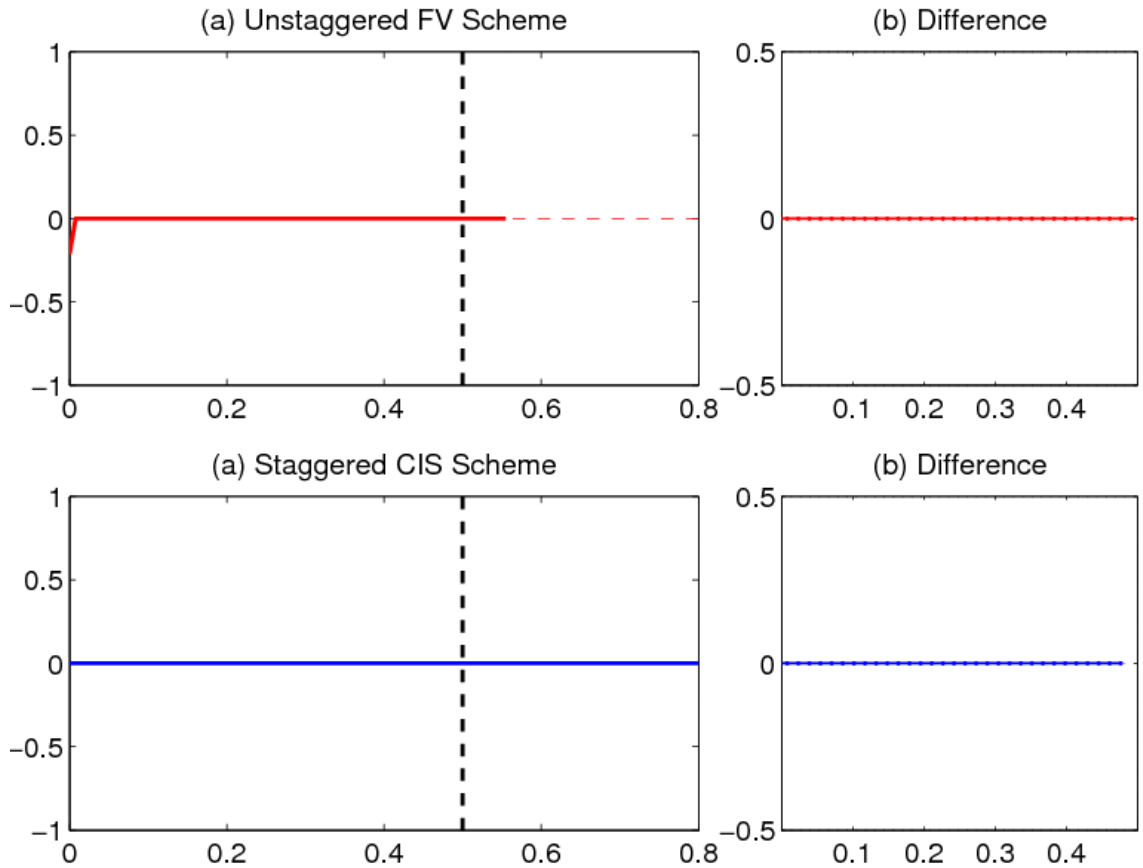


Multi-Resolution Models

Three theoretical "requirements" for multi-resolution modeling:

1. Arakawa A-Grid or Z-Grid (Unstaggered Grid)
2. Explicit diffusion at refinement boundaries
3. High-order accuracy

Grid Interface Wave Reflection

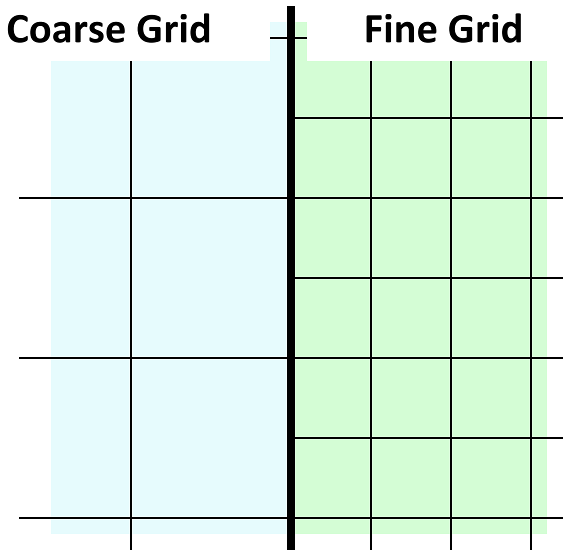


Source: Ullrich and Jablonowski (2010) "An analysis of 1D finite-volume methods for geophysical problems on refined grids." J. Comp. Phys.

Why High-Order Accuracy?

- Many current generation models are only second-order accurate; that is, state variables are approximately linear.

- In the presence of mesh refinement, numerical methods generally lose one order of accuracy (equivalent to state variables approximately constant).



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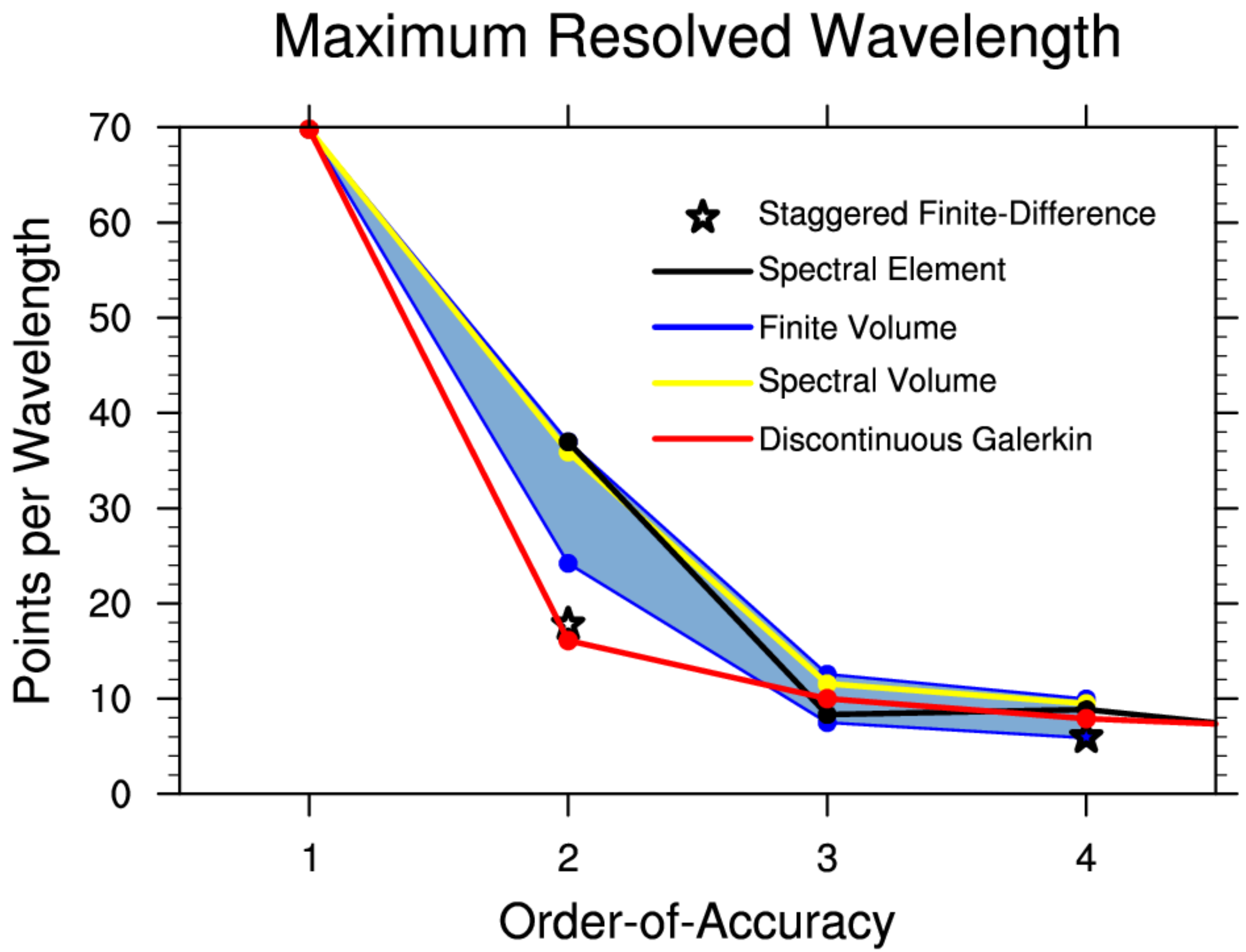
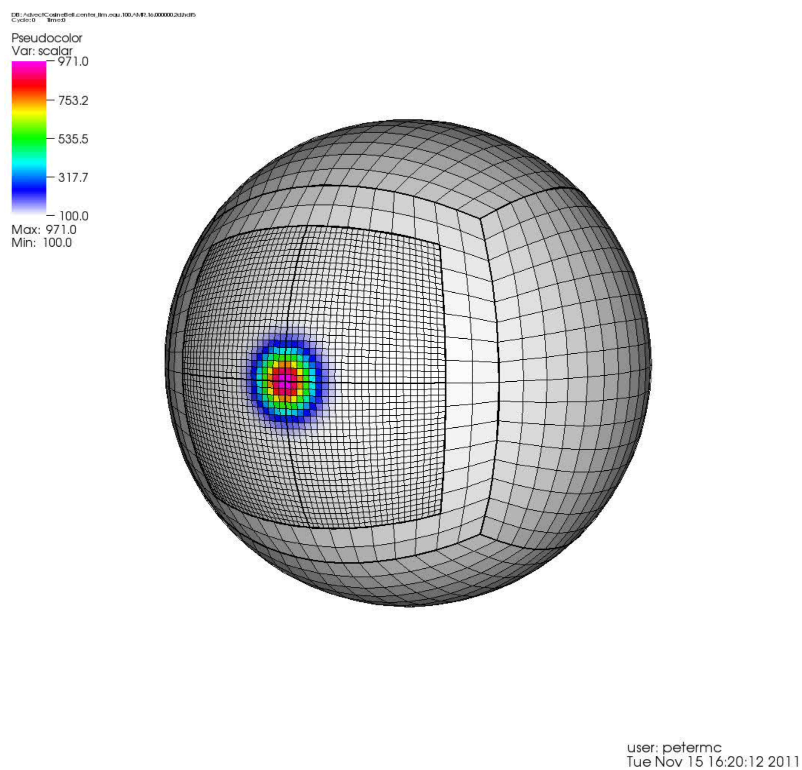


Mesh Refinement

Since the MCore / Chombo model uses non-conformal grids, the grid may be actively adapted to follow features of interest.



Summary

Our methods have been shown to be accurate and robust when applied to a vast array of test problems on a variety of scales (microscale to global scale).

Further, design considerations suggest these methods should scale well on massively parallel systems.

MCore is undergoing rapid development with the goal of operational deployment in the next few years.

Affiliated Projects

Several projects are now underway which use the MCore framework as applied to a variety of geophysical problems:

- ***Ocean basin and biological transport modeling***
  with Dr. Francis Poulin (University of Waterloo)
- ***Upper atmosphere thermosphere / ionosphere modeling***
  with Dr. Aaron Ridley (University of Michigan)
- **Non-hydrostatic model intercomparison testing**
  with Drs. Andrew Staniforth and Nigel Wood (UK Met Office)
- ***Cloud system resolution and feedback studies***
  with Dr. Joyce Penner (University of Michigan)

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Thank You