Progress towards an Adaptively Refined Atmospheric Model

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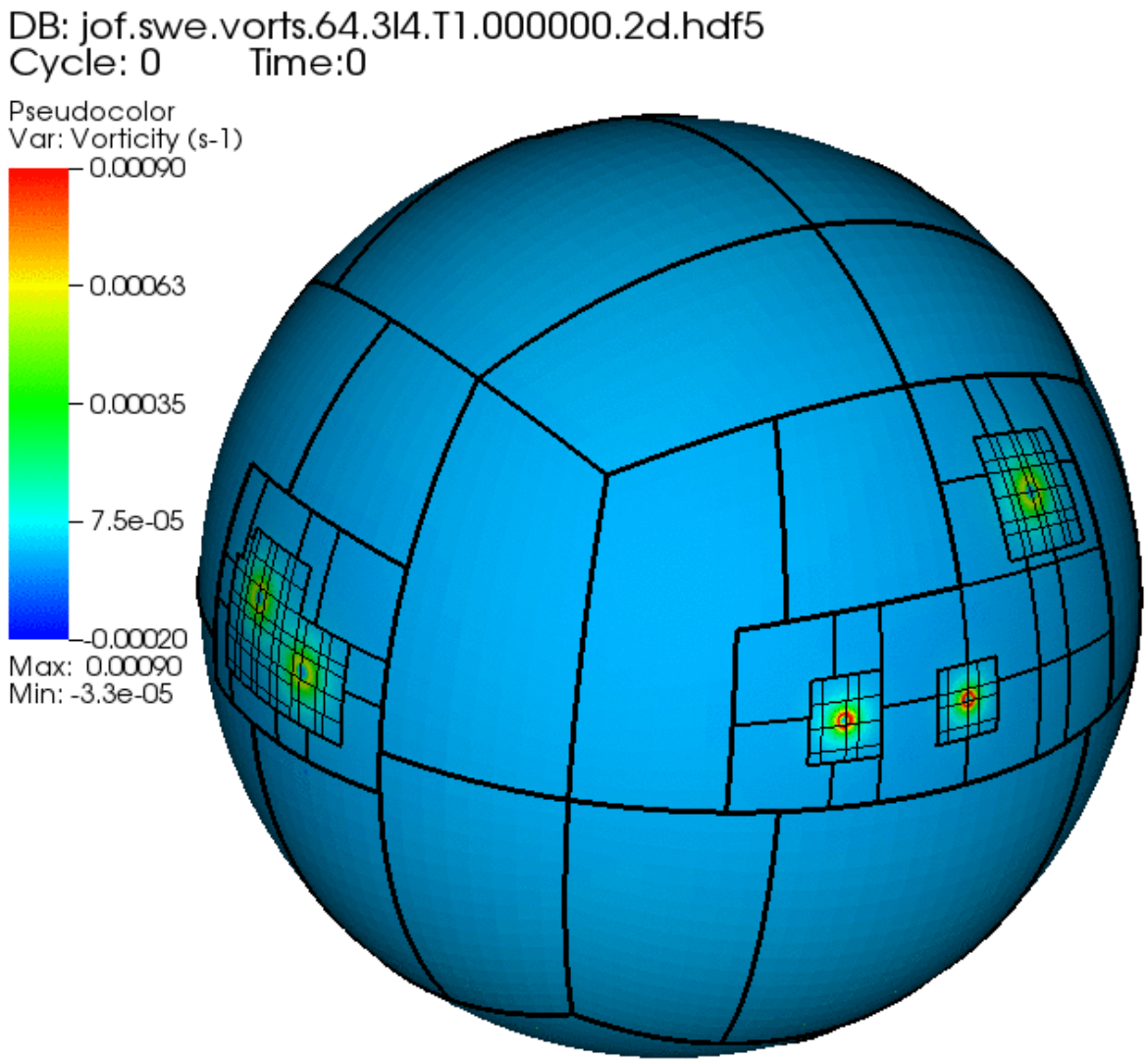
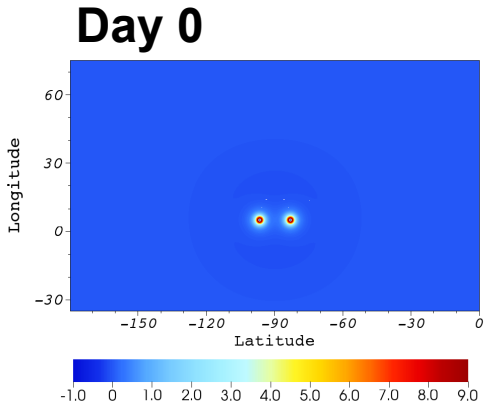
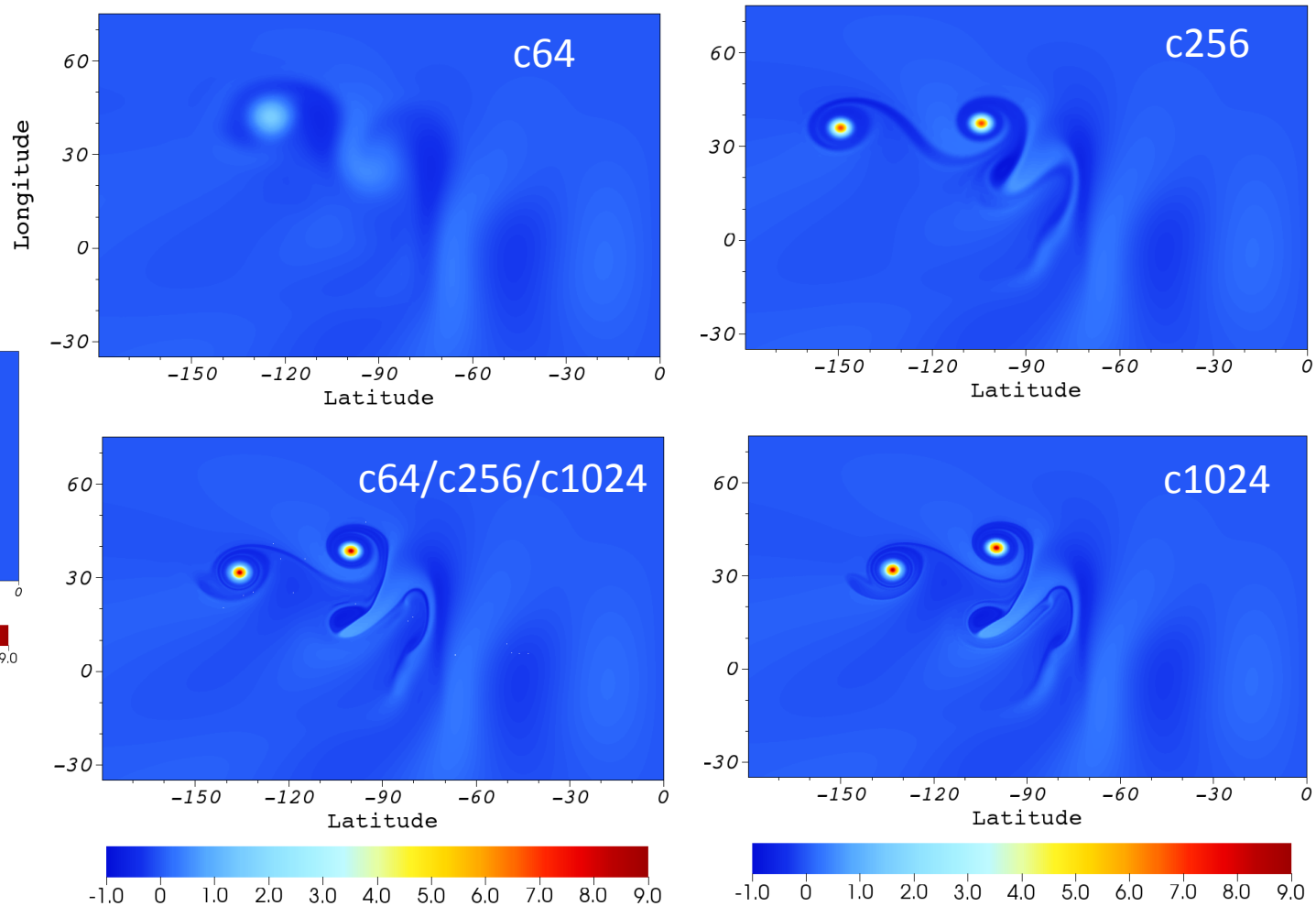
Adaptive Mesh Refinement



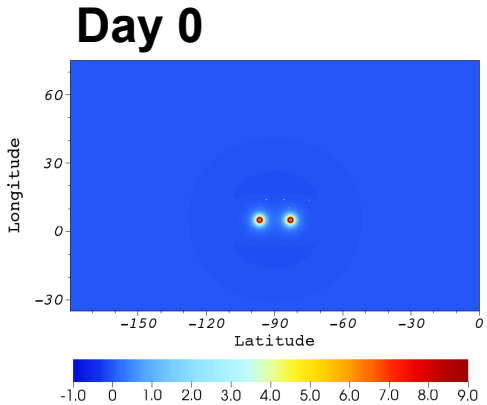
Adaptive Mesh Refinement

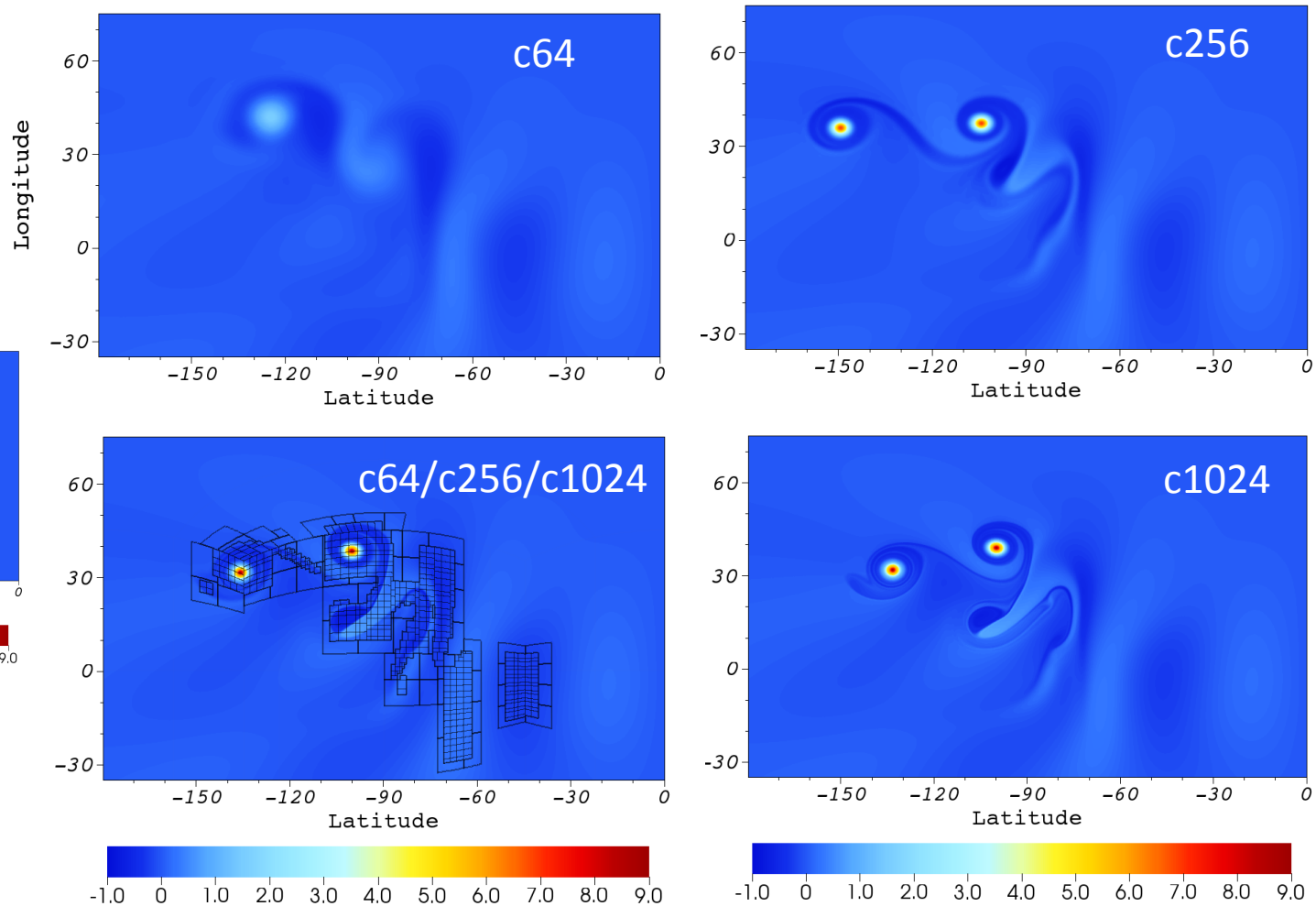




Day 6

Adaptive Mesh Refinement

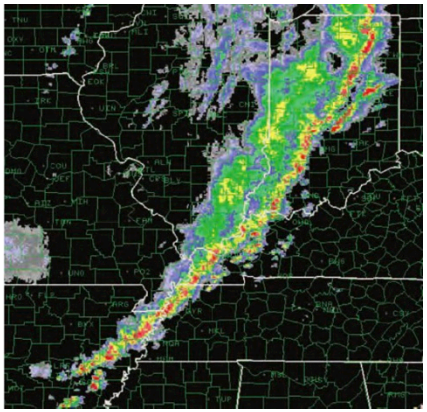


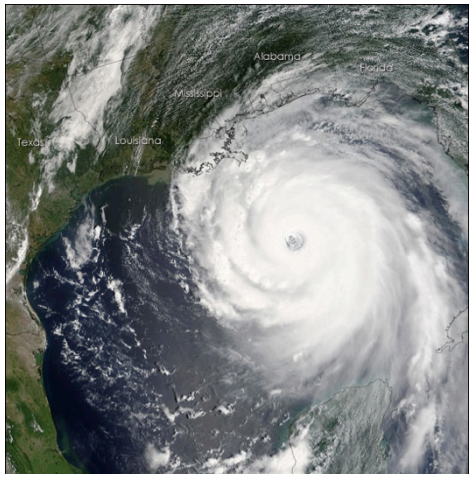


Day 6

Potential of Adaptive Mesh Refinement

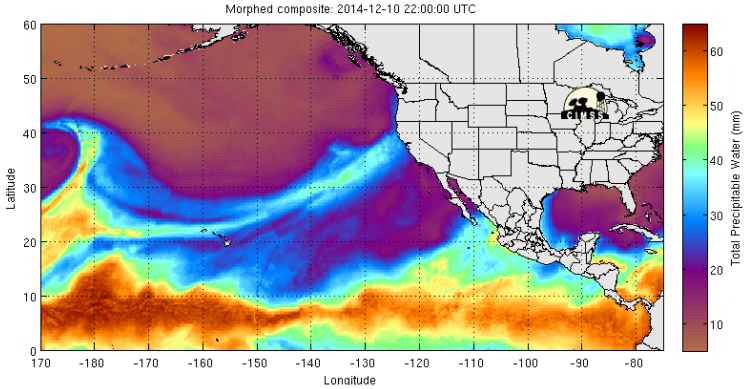
- Track and resolve small-scale and synoptic features while reducing computational cost.
- Ideal for local or regional dynamic features and weather phenomena (tropical cyclones, squall lines)
- AMR can serve as a test bed for physical parameterizations across a range of temporal and spatial scales





NASA's Earth Observatory

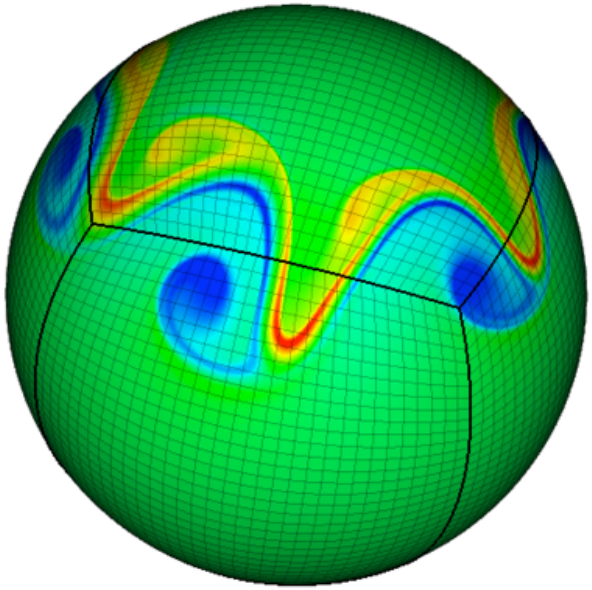
National Weather Service/NOAA



UW-Madison SSEC/CIMSS

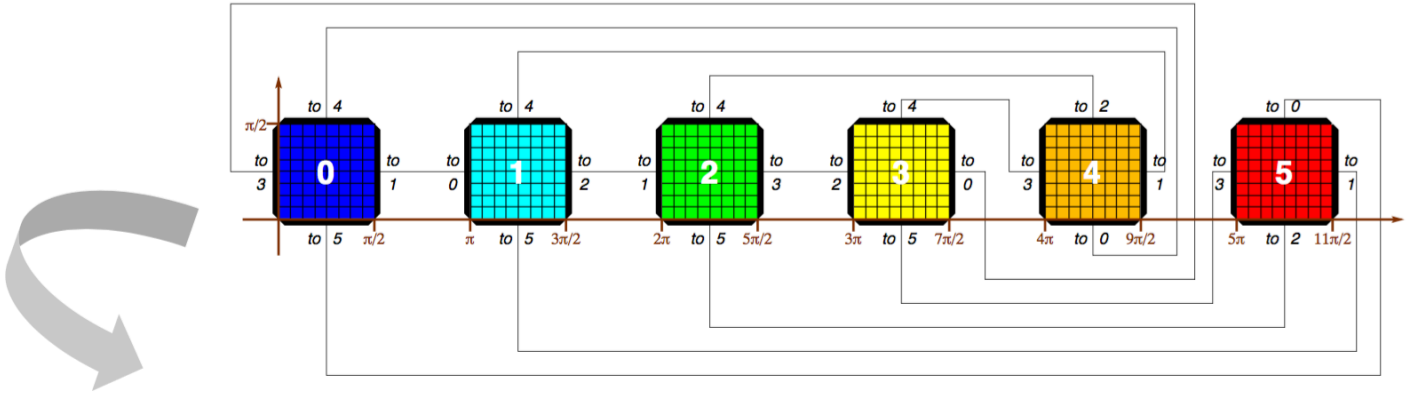
Features

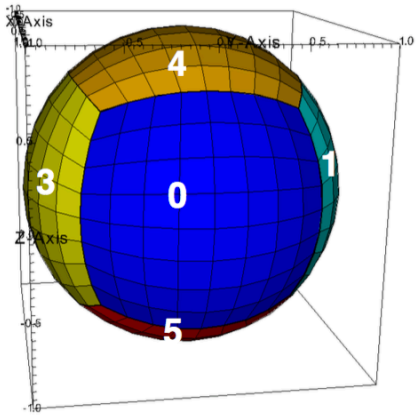
- **Non-hydrostatic**
- **Finite Volume**
  - 4th order horizontal, 2nd or 4th order vertical
- **Cubed-Sphere Grid**
- **Temporal discretization**:
  - Split explicit / implicit
  - Terms for vertical acoustic waves treated implicitly
- **Adaptive Mesh Refinement**
  - Block-structure, h-refinement, in both horizontal and vertical
  - AMR grids are sub-cycled in time



Cubed-Sphere Grid

- Gnomonic (equiangular) cubed-sphere grid.
- Use a “multi-block” mapping between the cubed-sphere panels
- Use an arbitrary stretched grid in vertical direction





Prognostic State Variables for the dycore

$$\boldsymbol{S} = \begin{bmatrix} \langle J\rho u^{\alpha} \rangle \\ \langle J\rho u^{\beta} \rangle \\ [w]_f \\ [p]_c \\ \langle J\rho \rangle \\ \langle J\rho\theta_v \rangle \\ \langle J\rho q_v \rangle \\ \langle J\rho q_p \rangle \\ \langle J\rho q_t \rangle \\ \vdots \end{bmatrix}$$

Mapped horizontal momentum density

Face-centered vertical velocity

Staggered "implicit" variables

Cell-centered dynamic pressure

Mapped cell-average dycore variables / EoS

Jacobian-weighted FV cell averages for conserved variables, flux-divergence form:

$$-\sum_i \partial_i (J\rho\theta_v u^i)$$

Mapped cell-average physics/tracers

Non-hydrostatic Equations

$$\frac{\partial J\rho u^\alpha}{\partial t} = -\sum_i \partial_i(J\rho u^\alpha u^i + JG^{\alpha i}p) - \partial_\xi(J\rho u^\xi u^\alpha + JG^{\alpha\xi}p) + J\Psi_C^\alpha + J\Psi_M^\alpha$$

$$\frac{\partial J\rho u^\beta}{\partial t} = -\sum_i \partial_i(J\rho u^\beta u^i + JG^{\beta i}p) - \partial_\xi(J\rho u^\xi u^\beta + JG^{\beta\xi}p) + J\Psi_C^\beta + J\Psi_M^\beta$$

$$\frac{\partial w}{\partial t} = -\sum_i u^i\partial_i w - u^\xi\,\partial_\xi w - \frac{1}{\rho^{n+1}}\partial_r p^{n+1} - g$$

$$\frac{\partial p}{\partial t} = -\sum_i \left(\gamma p\frac{1}{J}\partial_i(Ju^i) + u^i\partial_i p\right) - u^\xi\partial_\xi p - \gamma p^{n+1}\,\partial_r w^{n+1} + \eta(P(\rho\theta_v)^{n+1} - p^{n+1})$$

$$\frac{\partial J\rho}{\partial t} = -\sum_i \partial_i(J\rho u^i) - \partial_\xi(J\rho u^\xi)$$

$$\frac{\partial J\rho\theta_v}{\partial t} = -\sum_i \partial_i(J\rho\theta_v u^i) - \partial_\xi(J\rho\theta_v u^\xi)$$

$$\frac{\partial J\rho q_v}{\partial t} = -\sum_i \partial_i(J\rho q_v u^i) - \partial_\xi(J\rho q_v u^\xi)$$

Non-hydrostatic / vertical implicit approach

$$\frac{\partial w}{\partial t} = -\sum_i u^i \partial_i w - u^\xi \partial_\xi w - \frac{1}{\rho^{n+1}} \partial_r p^{n+1} - g$$

Explicit "advection" operators

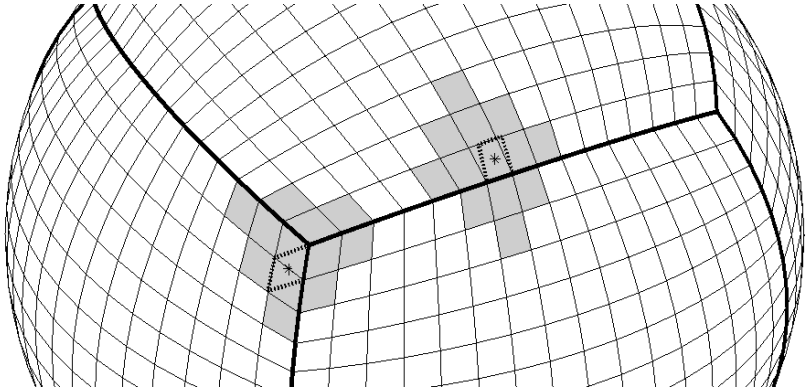
Staggered implicit "vertical" operators

$$\frac{\partial p}{\partial t} = -\sum_i \left(\gamma p \frac{1}{J} \partial_i (J u^i) + u^i \partial_i p \right) - u^\xi \partial_\xi p$$

$$- \gamma p^{n+1} \partial_r w^{n+1} + \eta (P(\rho\theta_v)^{n+1} - p^{n+1})$$

Unusual AMR dycore quirks …

[1] 3rd-order truncation error at cubed sphere boundaries from asymmetric stencils / fluxes:



[2] Non-linear (but fast) banded solve for p (in r direction only):

$$p^{n+1} - Cp^{n+1}\partial_r\left(\frac{1}{\rho^{n+1}}\partial_r p^{n+1}\right) = R_p$$

[3] "Volume discrepancy" term relaxes dynamic (prognostic) pressure to EoS:

$$+\,\eta(P(\rho\theta_v)^{n+1} - p^{n+1})$$

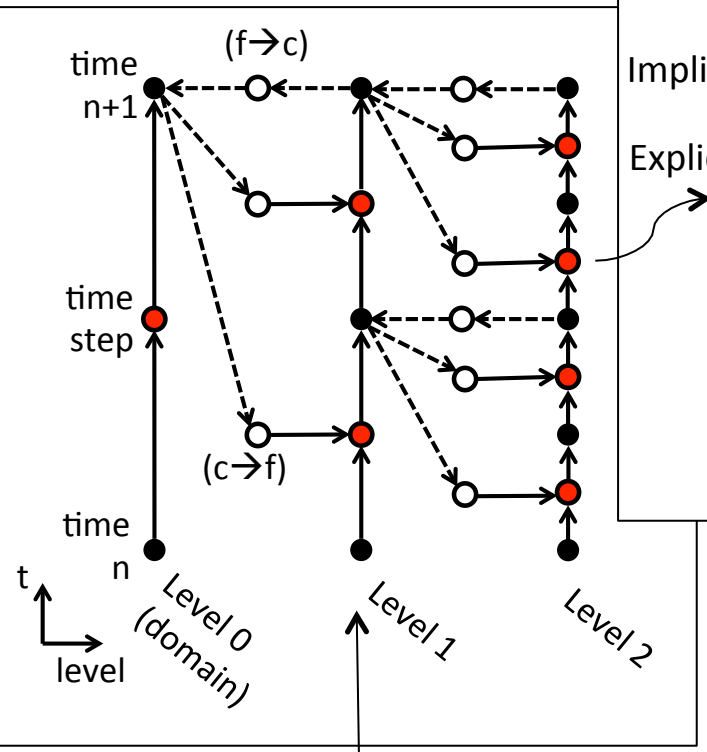
[4] 4th-order conversion to/from mapped averages to point-wise values "(de)convolution":

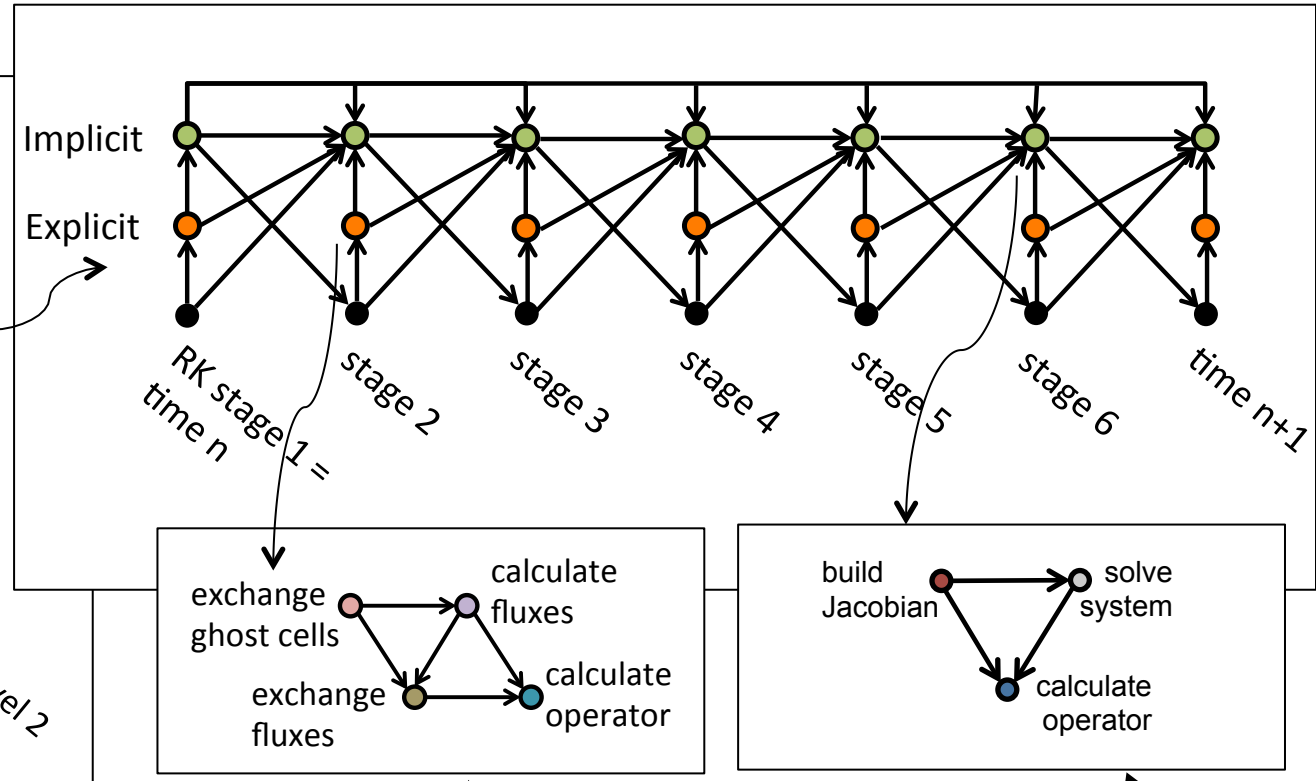
$$[S]_i = \langle S\rangle_i - \frac{1}{24}\sum_d \langle S\rangle_{i-e_d} - 2\langle S\rangle_i + \langle S\rangle_{i+e_d}$$

[5] Add 1D dissipation to face-average fluxes to help damp checkerboard modes:

$$-\left\langle J\rho u^i\phi\right\rangle_f + \boxed{\gamma v_{max}\langle J\rangle_f D_f^5\langle\rho\phi\rangle}$$

Anatomy of an AMR dycore time step …





Standard "subcycling" dynamic AMR algorithm, maintains conservation

4th-order explicit operator time step limited by CFL (horizontal compressible)

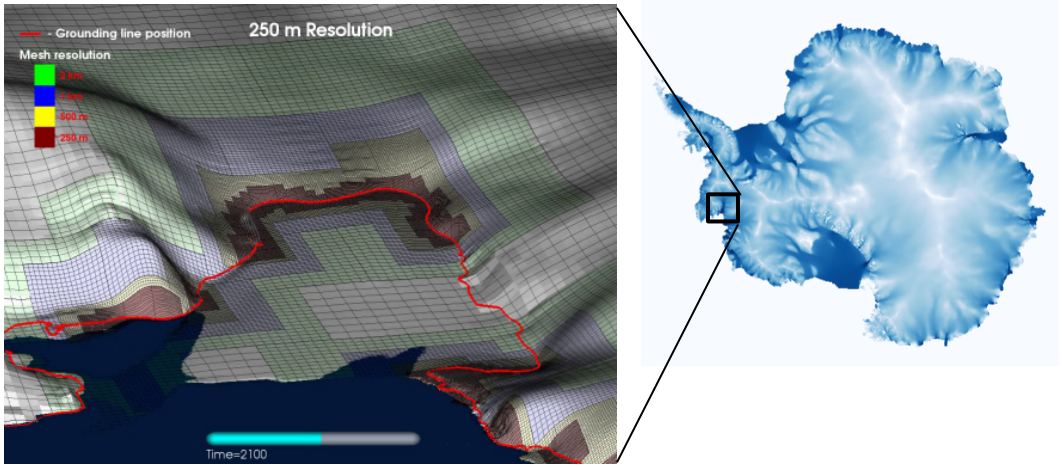
2nd or 4th-order implicit operator (no CFL constraint)

Chombo-AMR

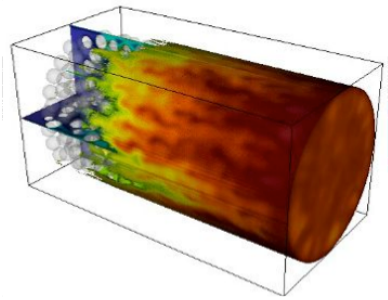
Uses the Chombo framework library:

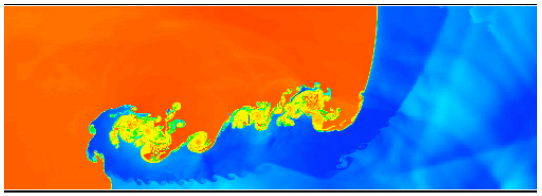
- *Open-source toolkit for solving PDES on structured grids*
- *Fast solvers minimize communication, memory access*
- *Scales to 100k+ processors with low-level details hidden*

Currently, there are a broad set of applications leveraging the Chombo framework with complex physics



BISICLES/LBNL

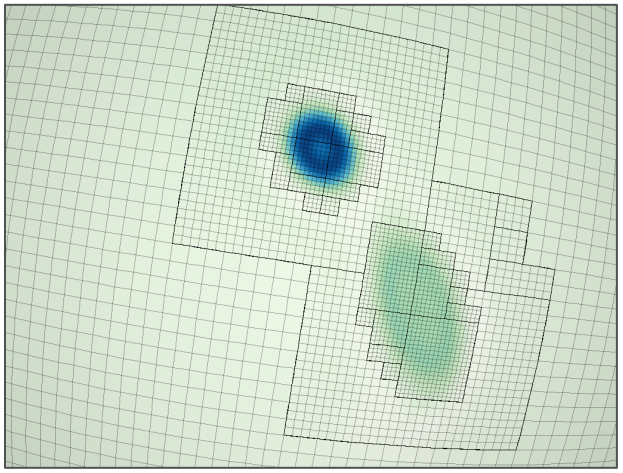


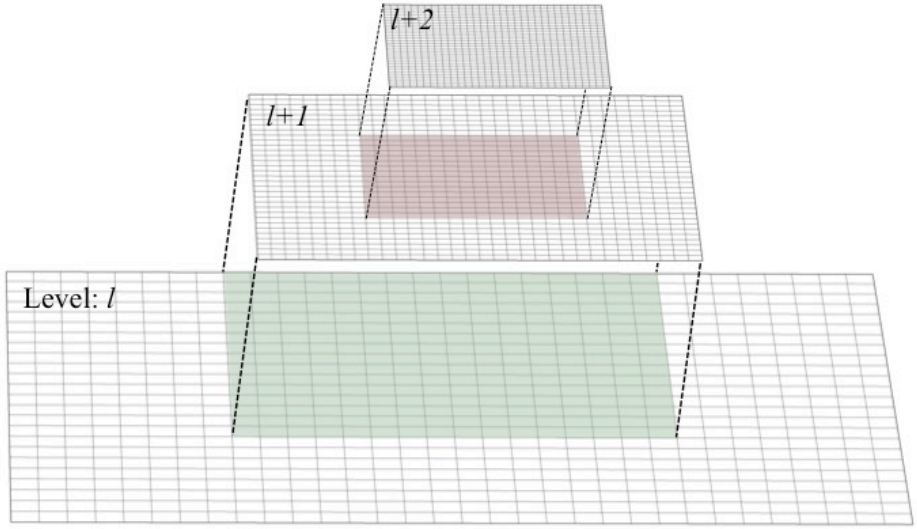


LBNL

Multi-block Refinement

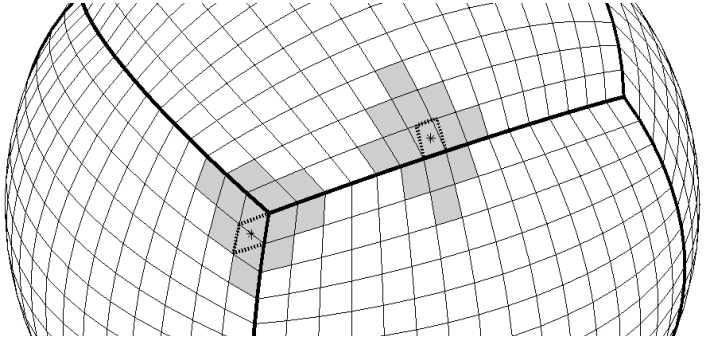
- Refinement grid levels are nested on coarse levels
- Up to ten levels of refinement and variable refinement ratio (e.g. x2, x4, x8)
- Intermediate levels must have sufficient number of cells between levels for ghost cell interpolation
- Refinement can be determined by various criteria:
  - *Height gradient, Vorticity, Tracer values, Topography, combinations*

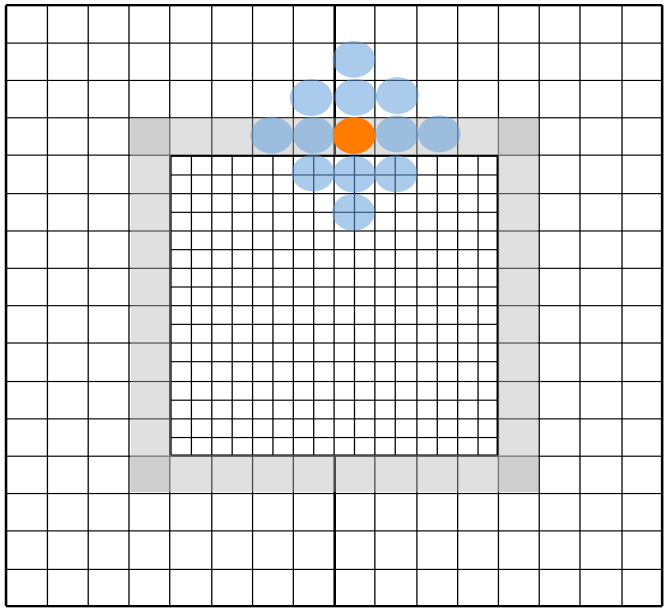




Ghost Cells

- 4th order least squares interpolation of conserved variables
- Extend domain with ghost cells at panel boundaries and coarse-fine boundaries
- Interpolated in space from stencil using least squares method
- Panel edges need 3 rows of ghost cells. Coarse-fine edges need at least 1 addition cell

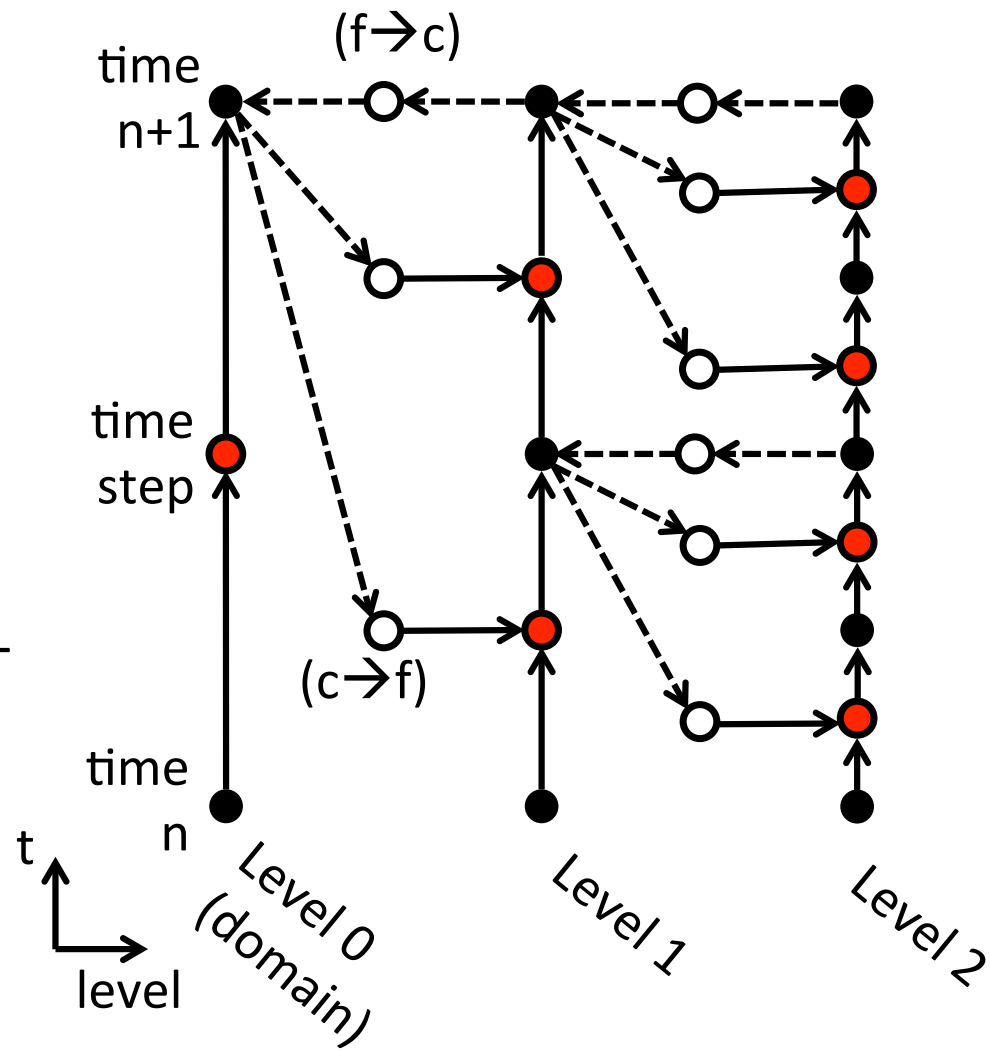




Time step sub-cycling

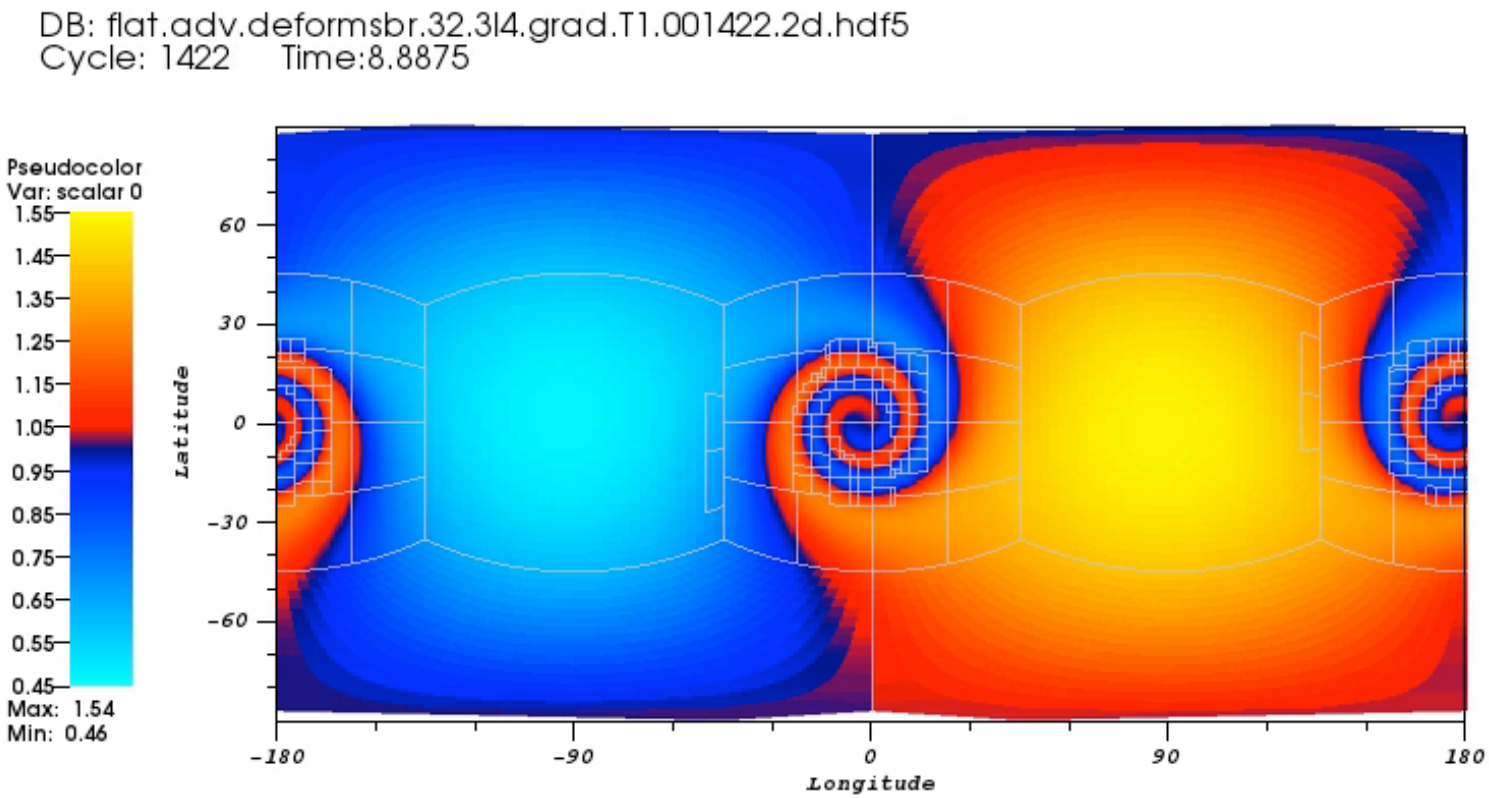
Advancing a level (*L*) in time:

1. Regrid finer levels if needed
2. Advance level L in time
3. Interpolate ghost cells for level L+1
4. Sub cycle level L+1 in time
5. Average solution from L+1 and correct fluxes at coarse-fine interface



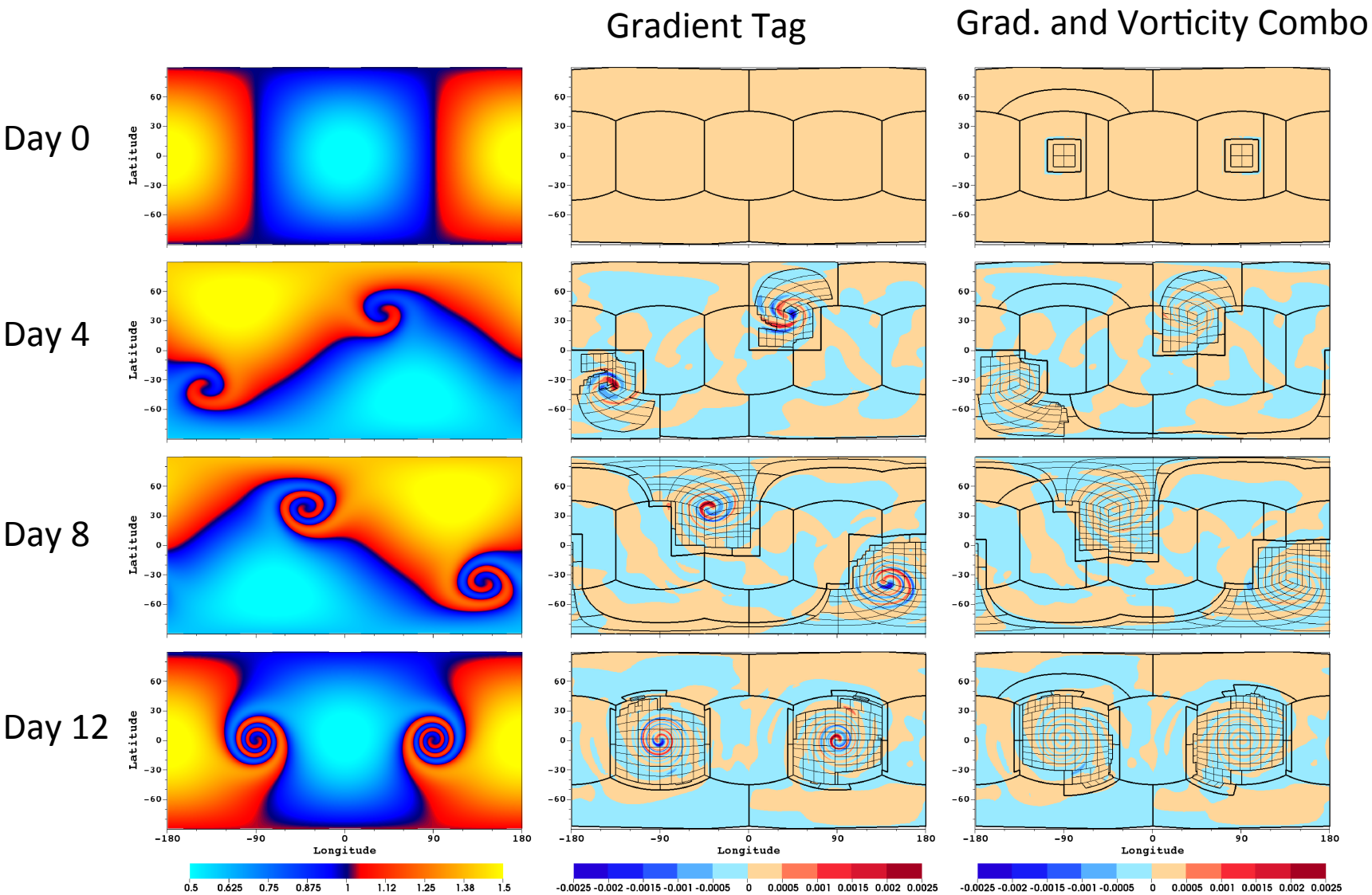
Advection Test: Moving Vortices

Advection test case in which an initially smooth passive tracer is rolled up into tight spiral bands over a 12 day period. (*Nair and Jablonowski, 2008*)



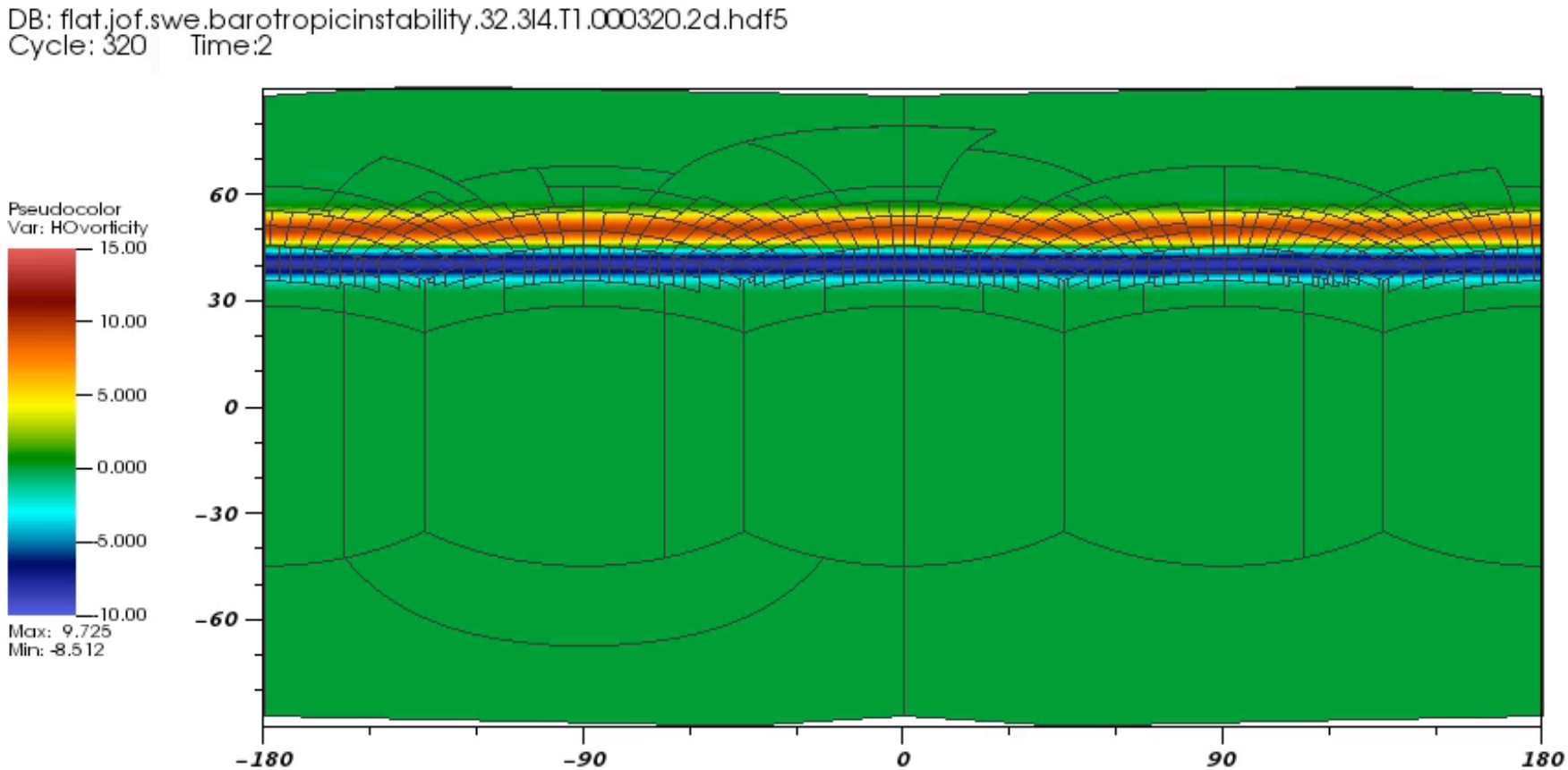
AMR c32/c128/c512 (from 310km to 20km)

Advection Test: Moving Vortices



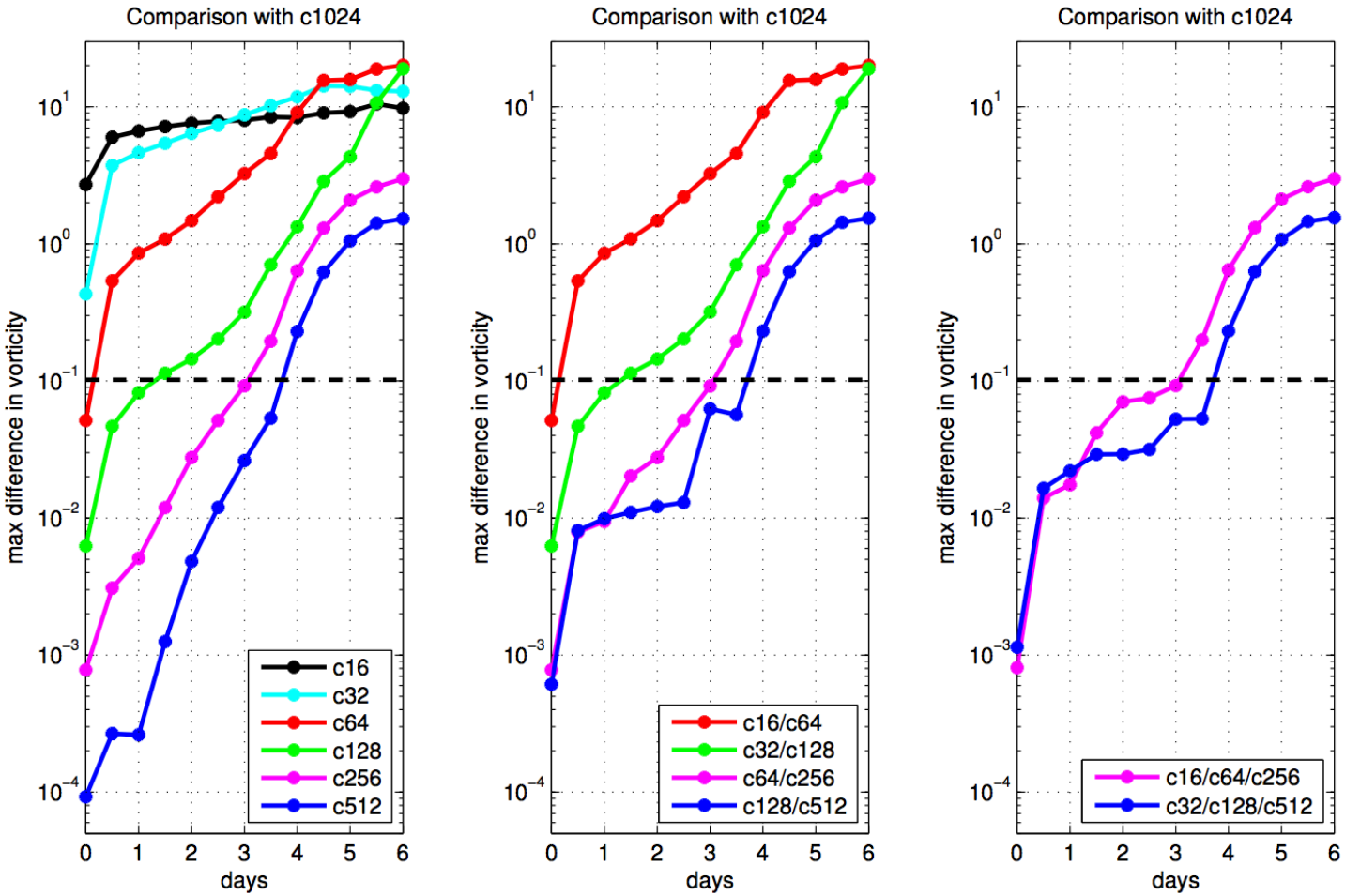
Shallow Water Test: Barotropic Instability

- *Galewsky et al. 2004*, barotropic instability test



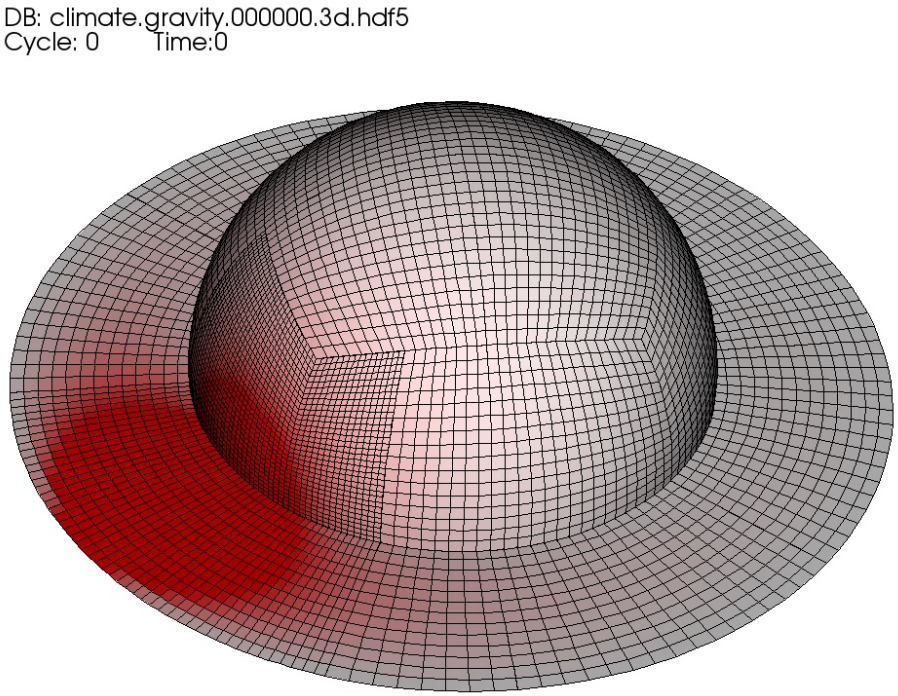
Shallow Water Test: Barotropic Instability

- Plots of maximum difference in relative vorticity (in units of day^{-1})
- Results from *McCorquodale, et al. 2015*

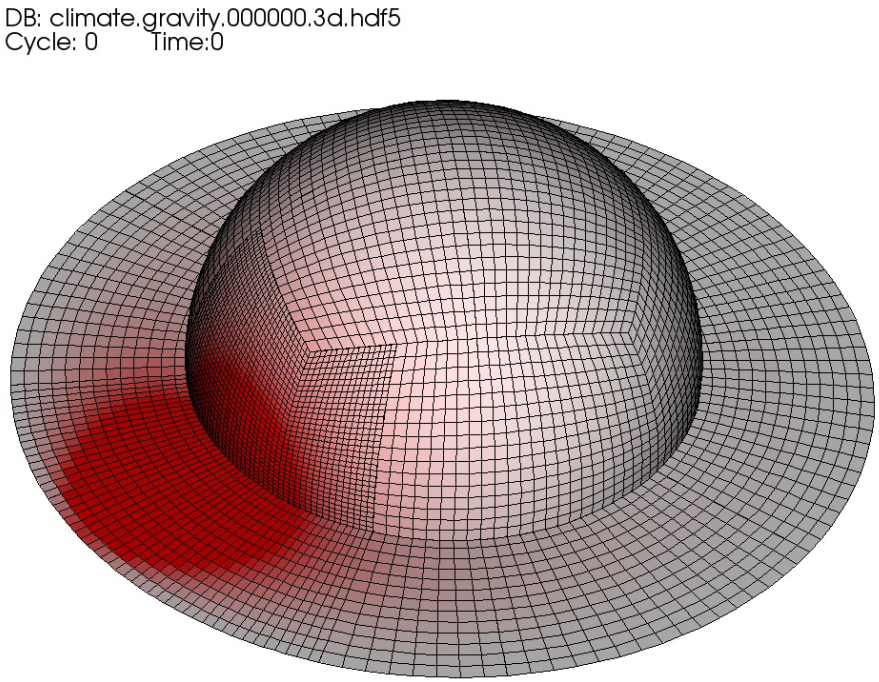


Nonorographic gravity waves

DCMIP-2012 Test 3-1: Potential Temp. perturbation at equator.



Potential Temperature perturbation



Pressure perturbation

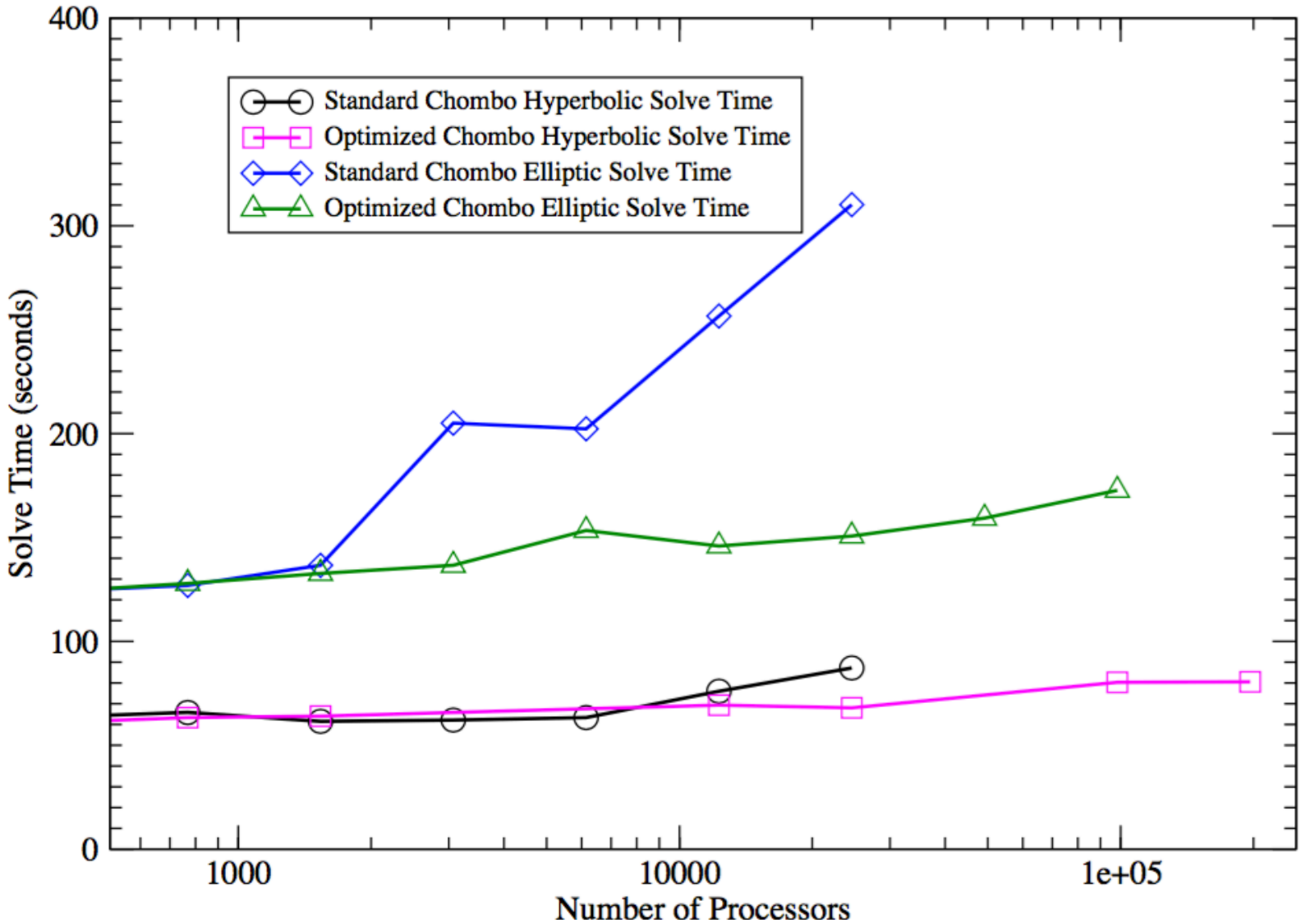
Ongoing and Future Work

- Finish implementing physics schemes: simple physics and SAM (System for Atmospheric Modeling) physics
  - Cell average tendencies are returned to the cubed-sphere
- Run DCMIP-2016 test cases
- Implement Topography

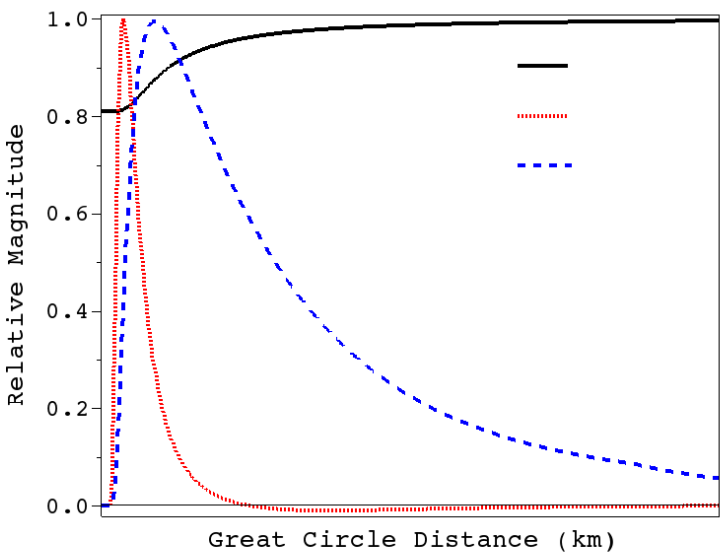
Thank You!

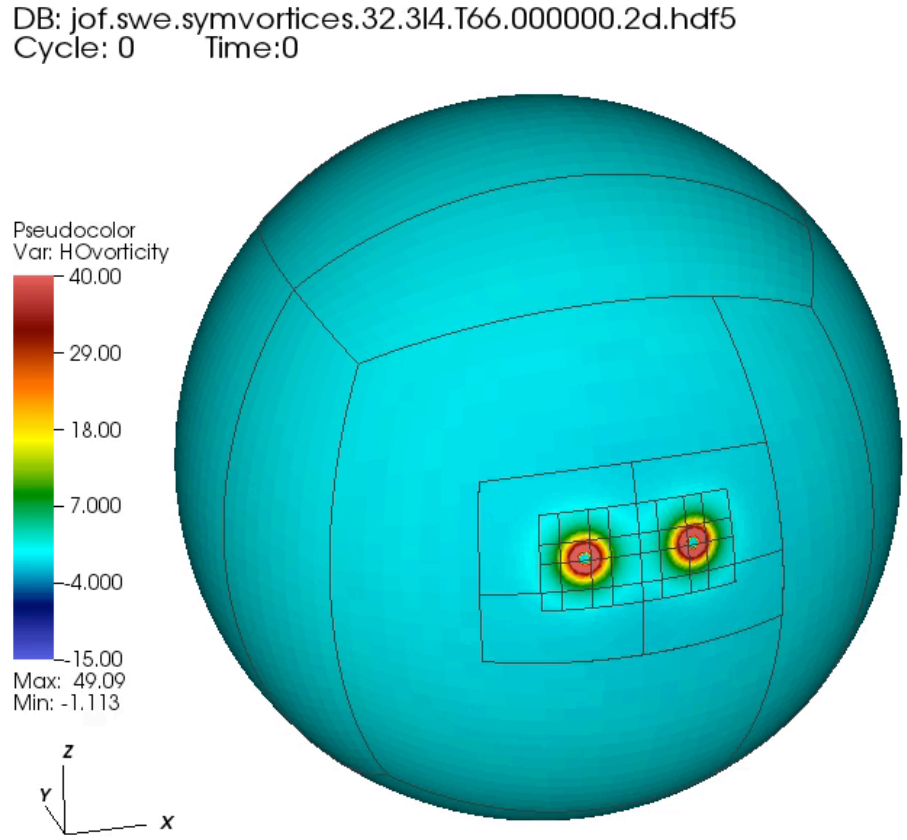
Extra Slides

Chombo-AMR Scaling



Shallow Water Test: Binary Vortices- Merging Case





Blue: Tangential Velocity, Red: Vorticity, and Black: Height field.