

# Progress towards an Adaptively Refined Atmospheric Model

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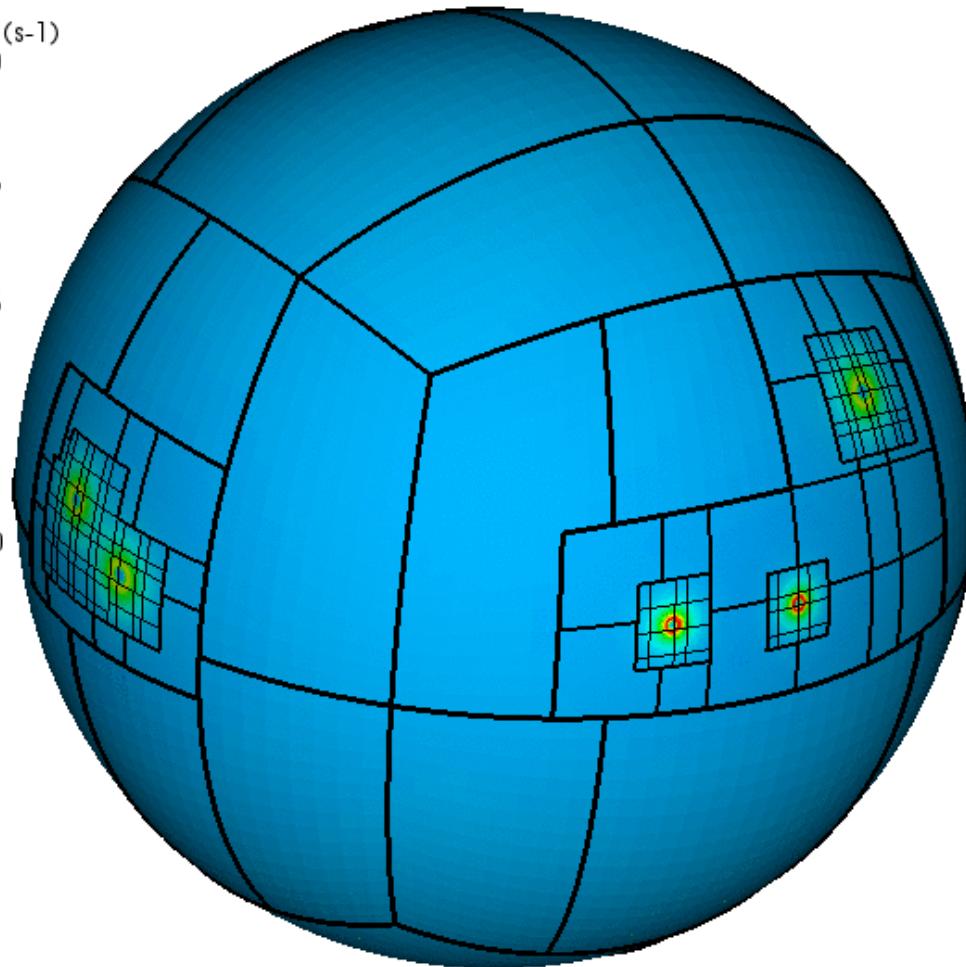
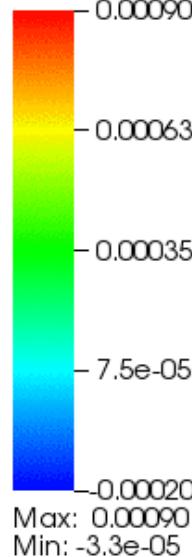
**P. Ullrich**

*U.C. Davis and Lawrence Berkeley Laboratory*

# Adaptive Mesh Refinement

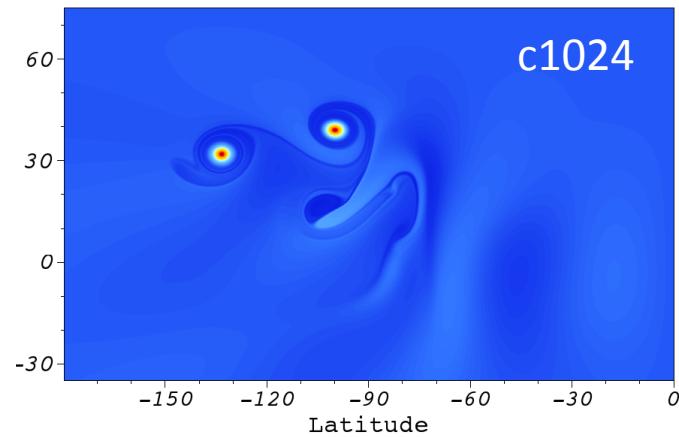
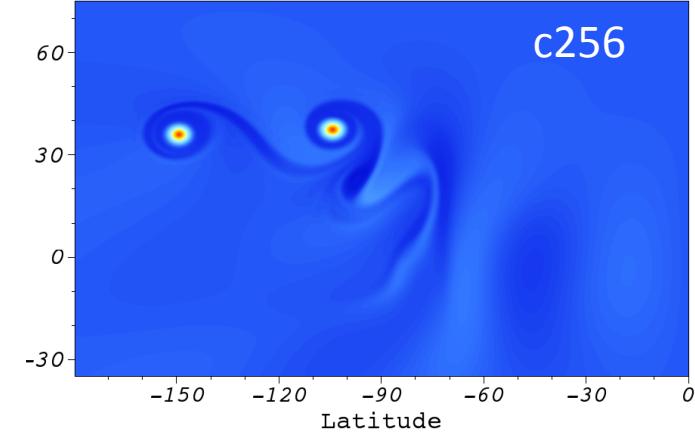
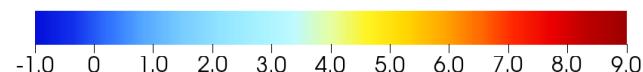
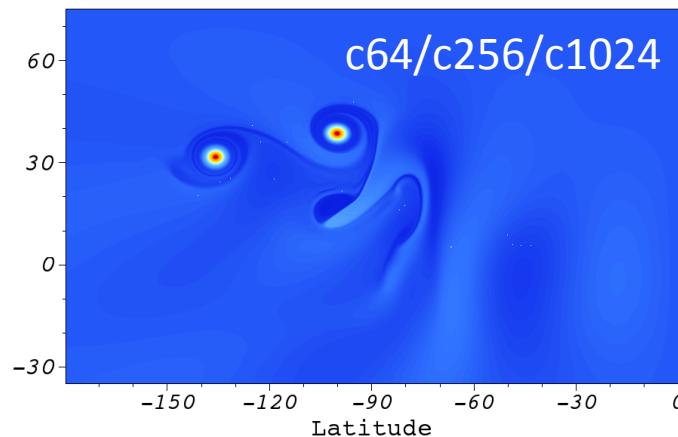
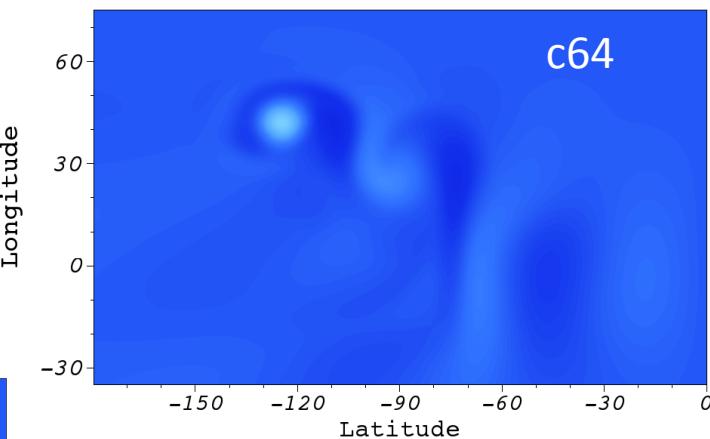
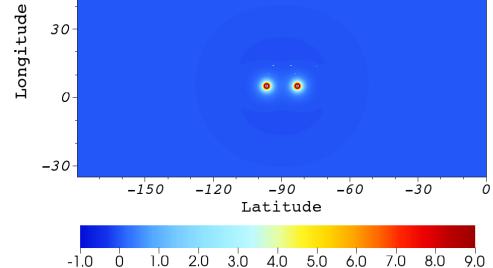
DB: jof.swe.vorts.64.3I4.T1.000000.2d.hdf5  
Cycle: 0 Time:0

Pseudocolor  
Var: Vorticity (s<sup>-1</sup>)



# Adaptive Mesh Refinement

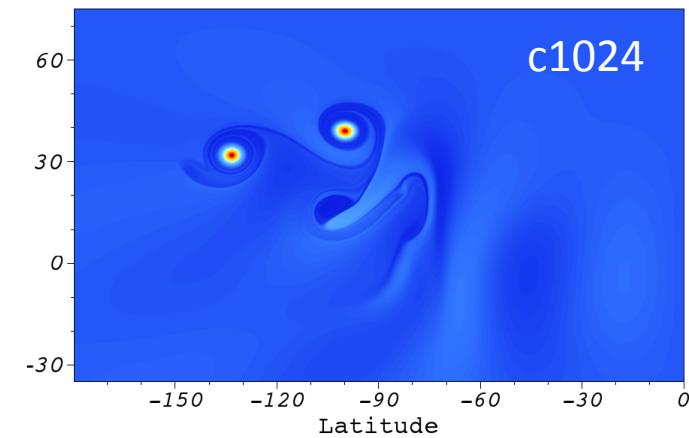
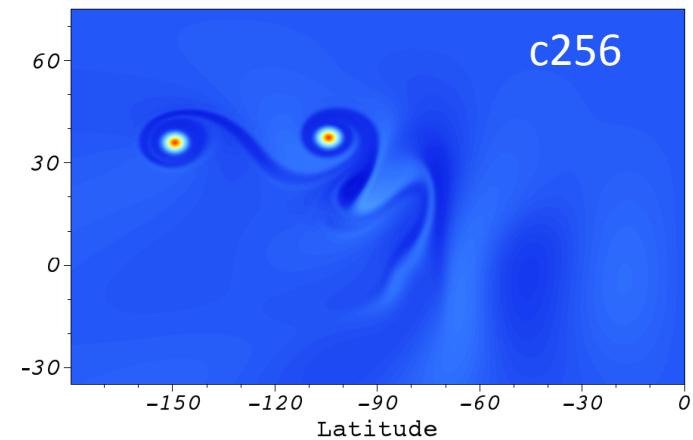
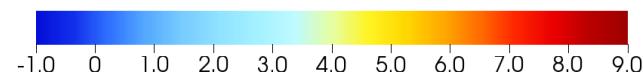
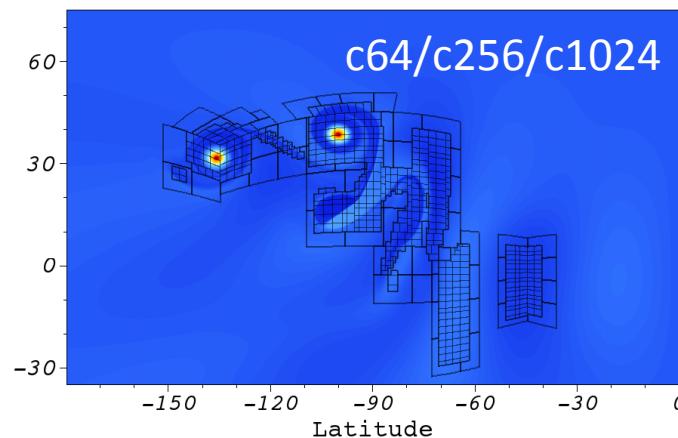
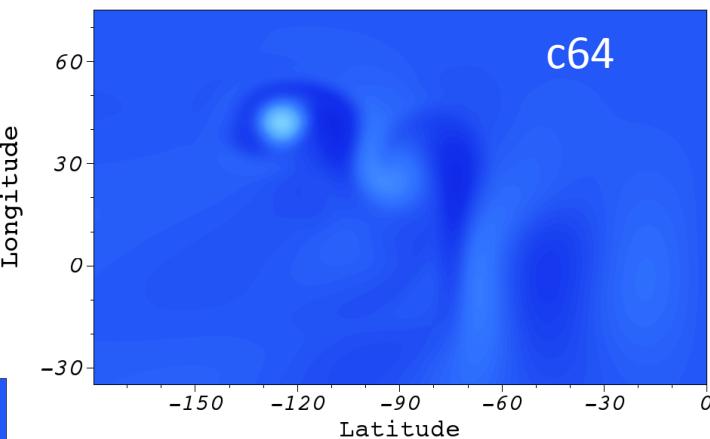
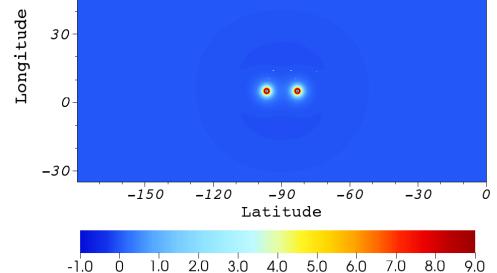
Day 0



Day 6

# Adaptive Mesh Refinement

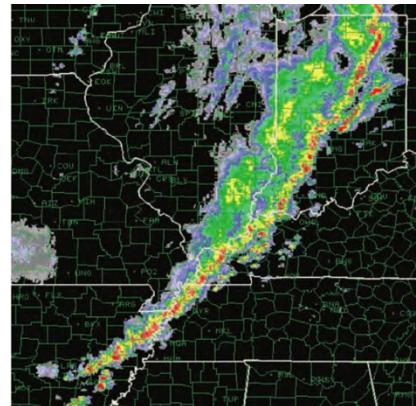
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Day 6

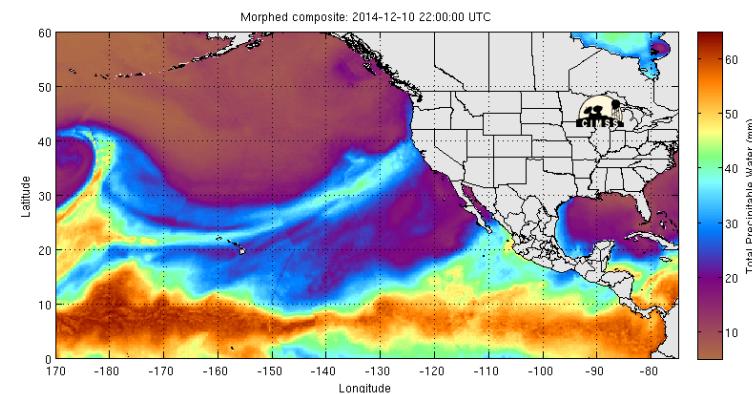
# Potential of Adaptive Mesh Refinement

- 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



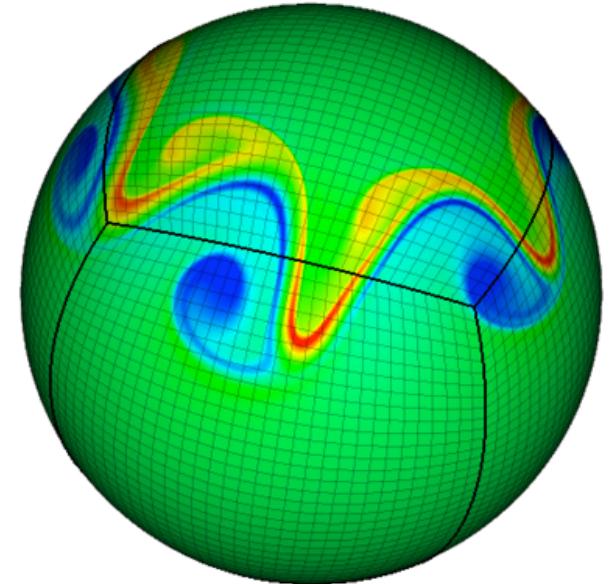
*NASA's Earth Observatory*

*National Weather Service/NOAA*



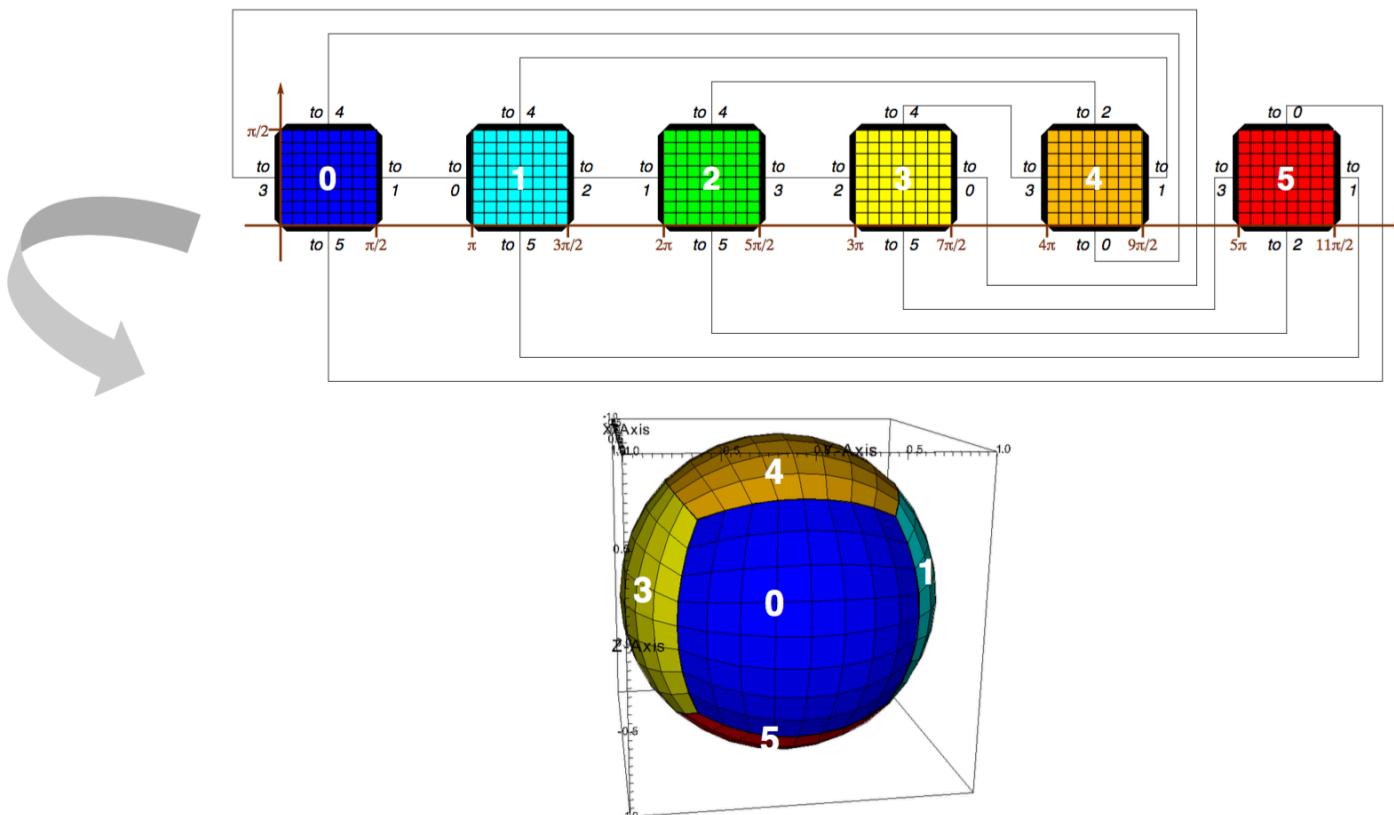
*UW-Madison SSEC/CIMSS*

- **Non-hydrostatic**
- **Finite Volume**
  - 4<sup>th</sup> order horizontal, 2<sup>nd</sup> or 4<sup>th</sup> 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

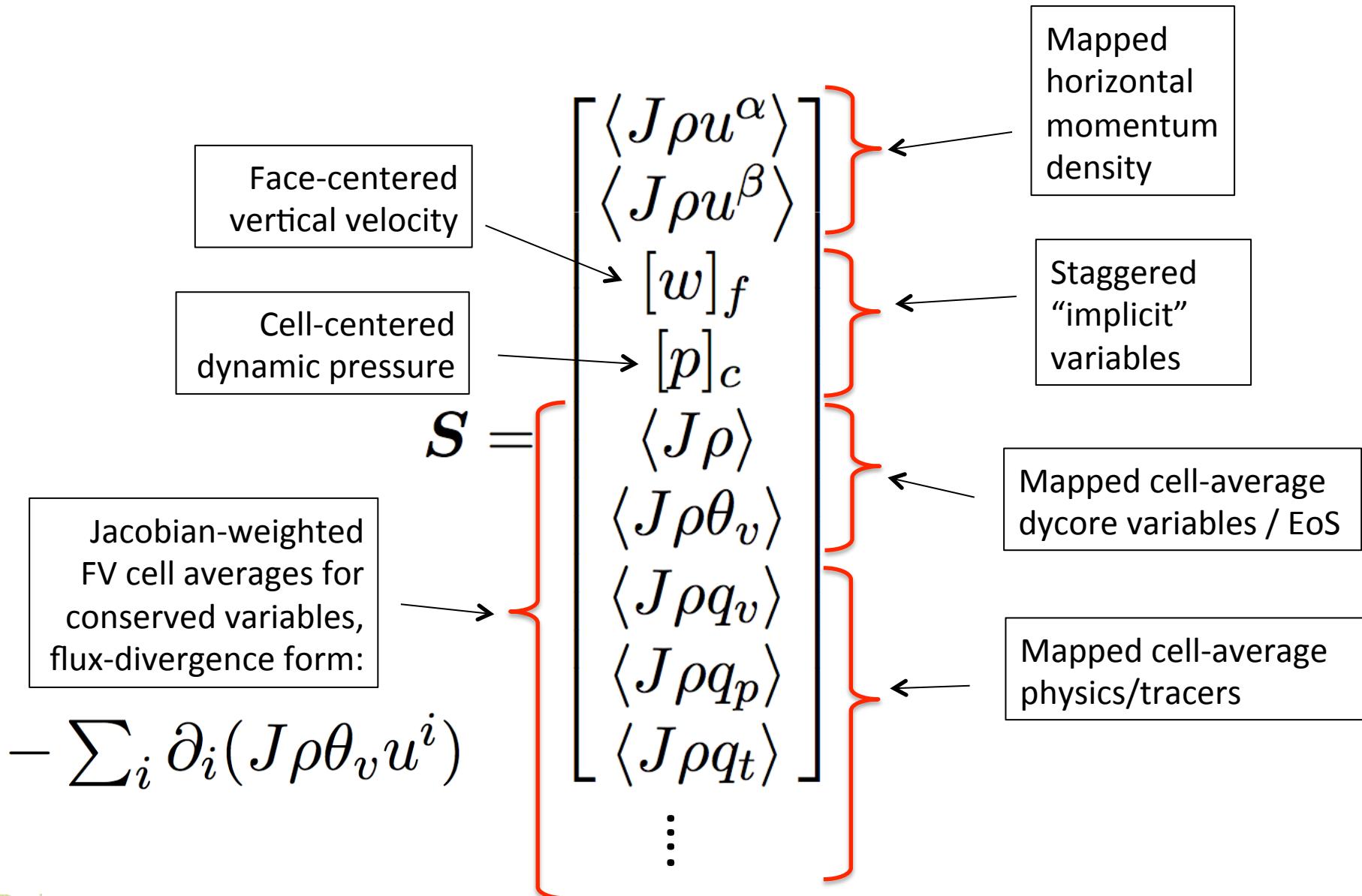


# Cubed-Sphere Grid

- 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



# 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

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

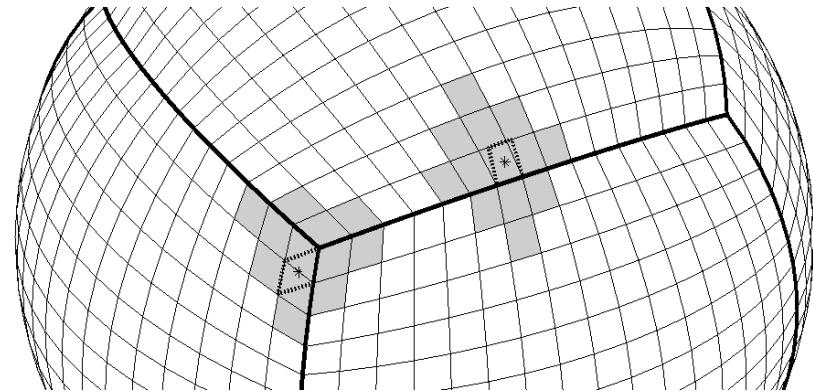
Explicit  
“advection”  
operators

Staggered  
implicit  
“vertical”  
operators

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

# Unusual AMR dycore quirks ...

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



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

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

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

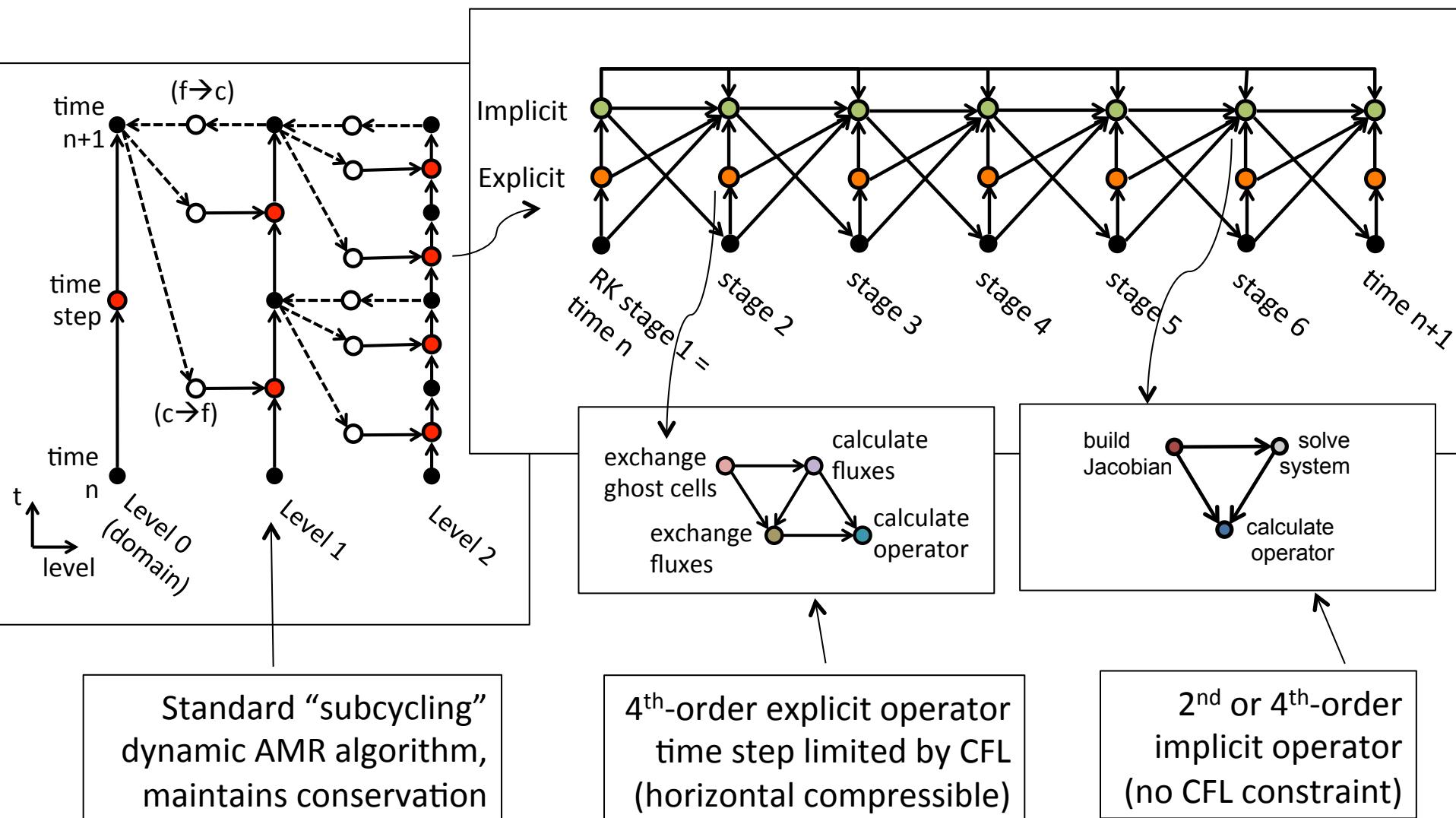
$$[S]_i = \langle S \rangle_i - \frac{1}{24} \sum_d \langle S \rangle_{i-e_d} - 2 \langle S \rangle_i + \langle S \rangle_{i+e_d}$$

[3] “Volume discrepancy” term relaxes dynamic (prognostic) pressure to EoS:  
 $+ \eta(P(\rho\theta_v)^{n+1} - p^{n+1})$

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

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

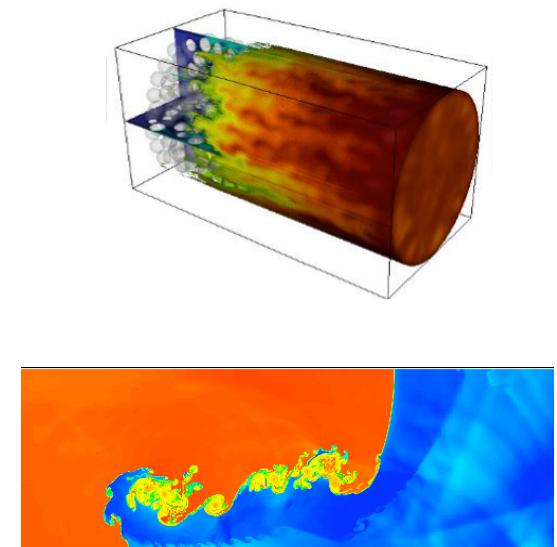
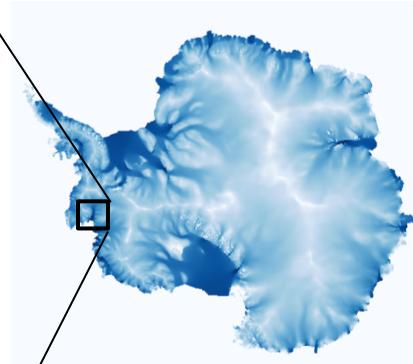
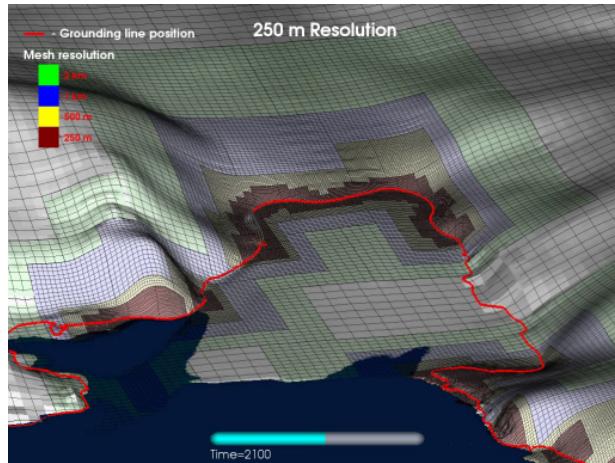
# Anatomy of an AMR dycore time step ...



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

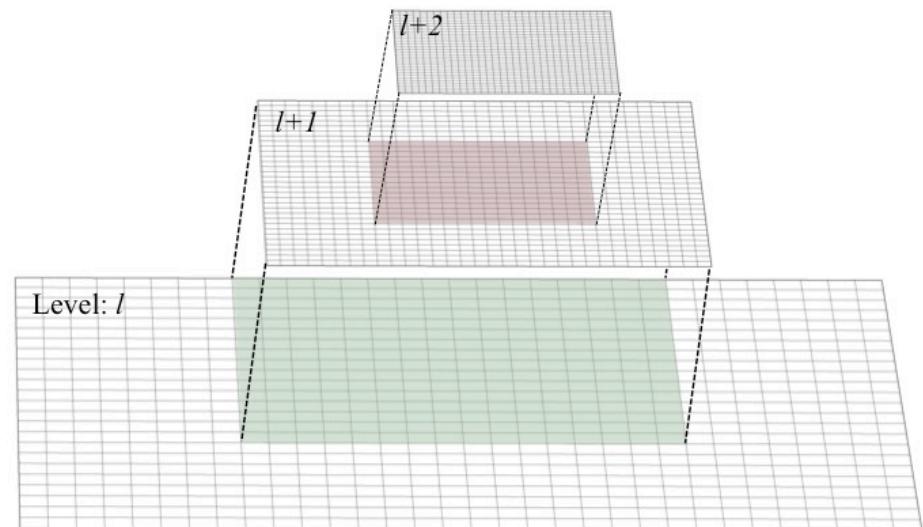
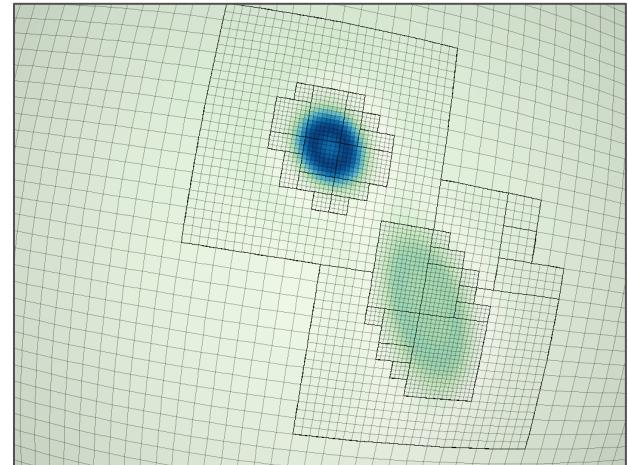
Currently, there are a broad set of applications leveraging the Chombo framework with complex physics



LBNL

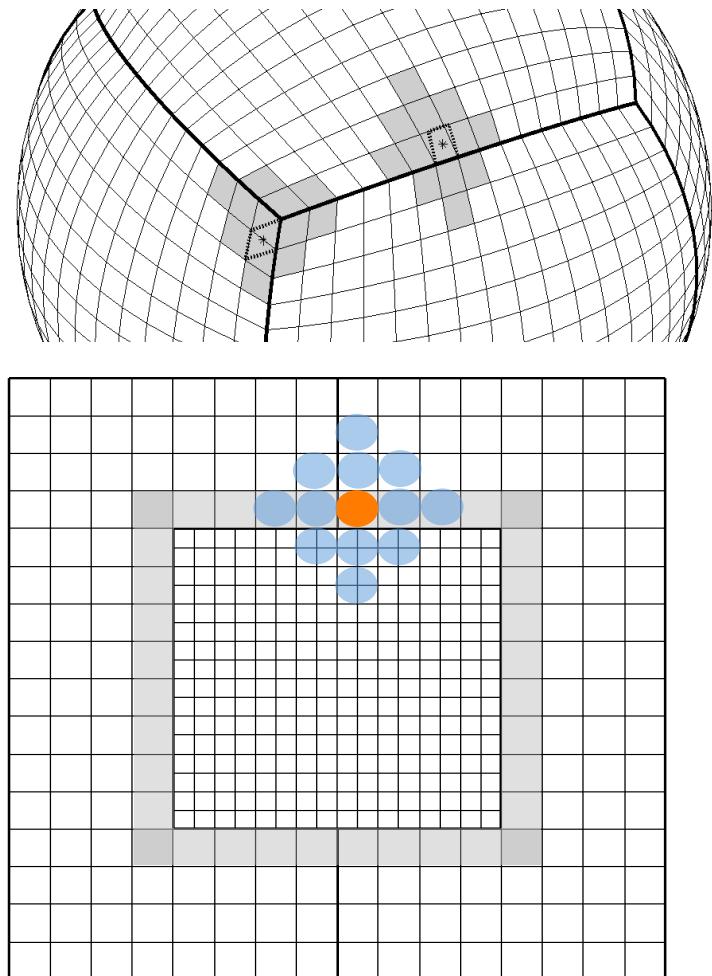
# Multi-block Refinement

- 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

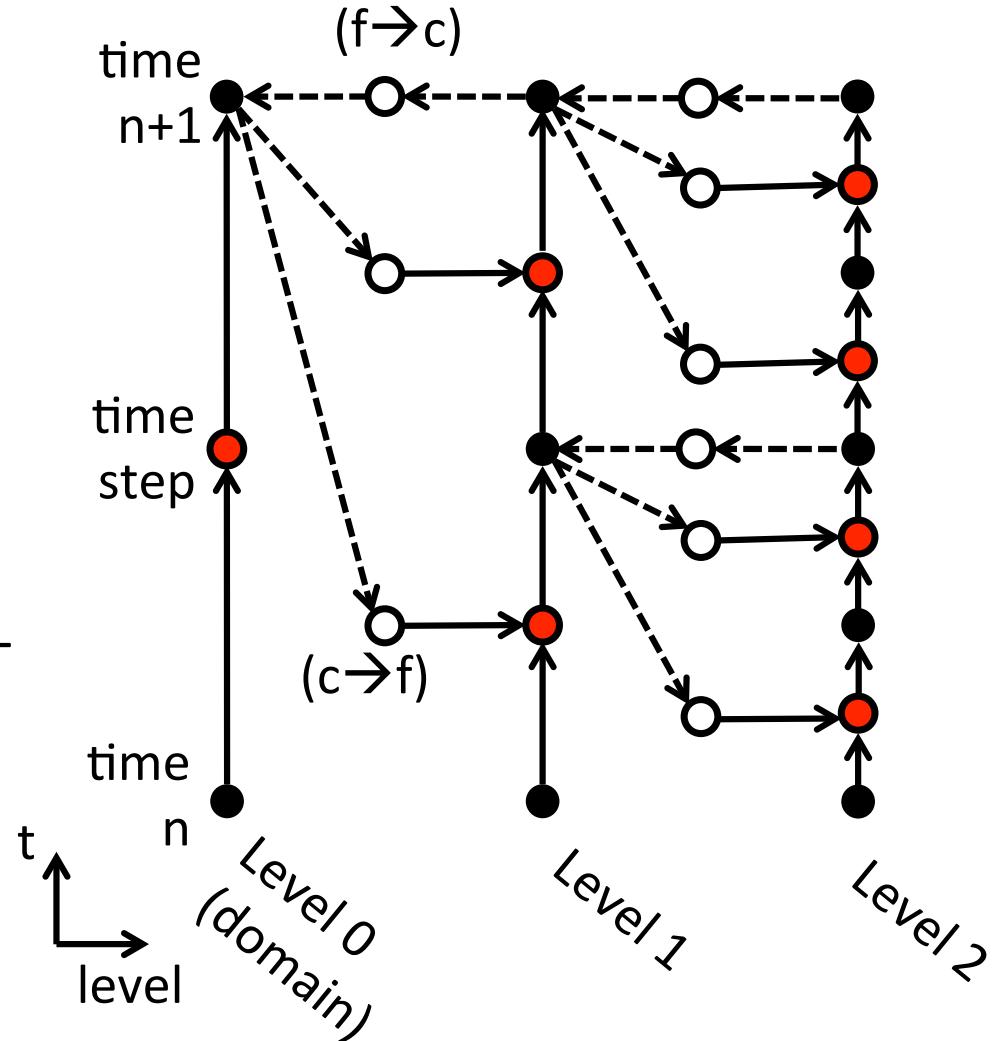
- 4<sup>th</sup> order least squares interpolation of conserved variables
- Extend domain with ghost cells at panel boundaries and coarse-fine boundaries
- Interpolated in space from stencil using least squares method
- Panel edges need 3 rows of ghost cells. Coarse-fine edges need at least 1 addition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



# Time step sub-cycling

## Advancing a level ( $L$ ) in time:

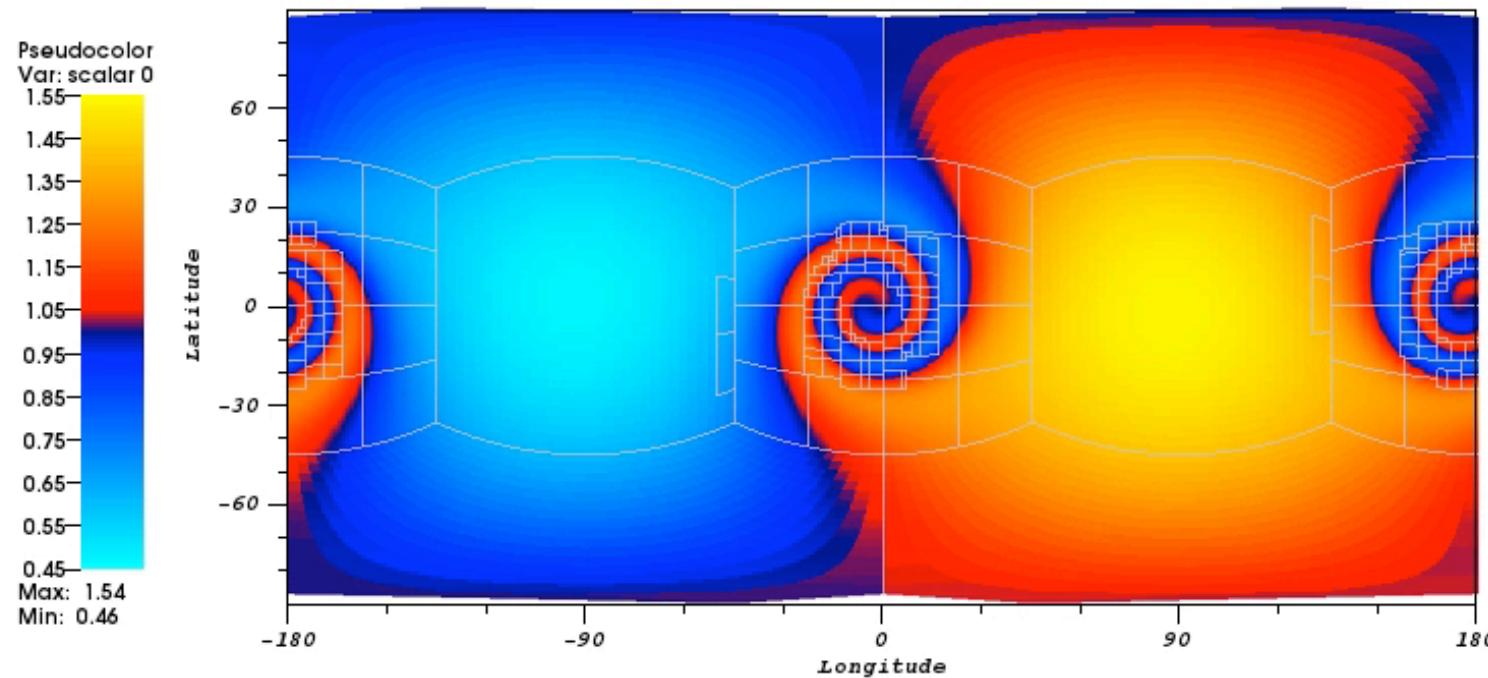
1. Regrid finer levels if needed
2. Advance level  $L$  in time
3. Interpolate ghost cells for level  $L+1$
4. Sub cycle level  $L+1$  in time
5. Average solution from  $L+1$  and correct fluxes at coarse-fine interface



# Advection Test: Moving Vortices

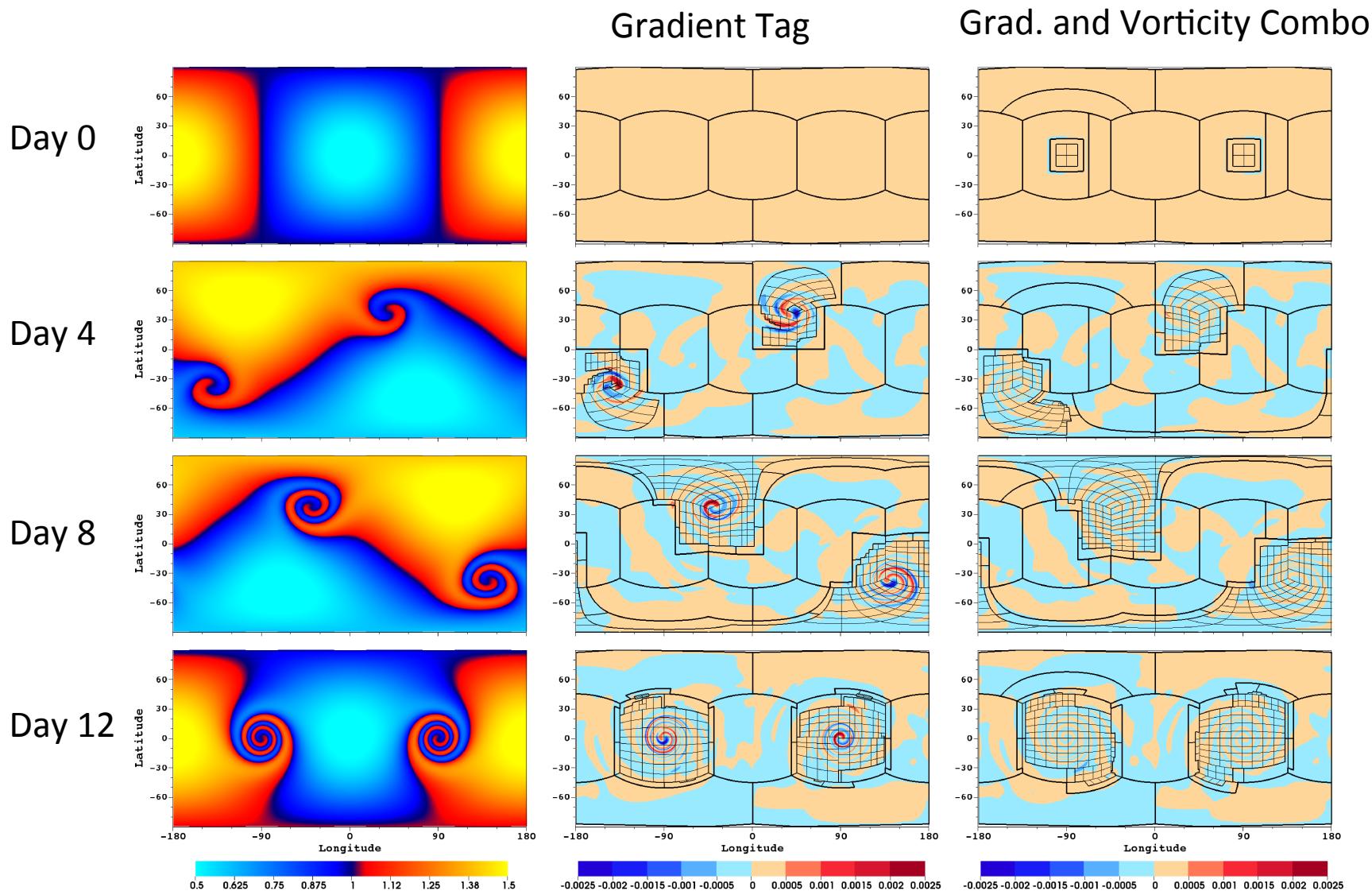
Advection test case in which an initially smooth passive tracer is rolled up into tight spiral bands over a 12 day period. (*Nair and Jablonowski, 2008*)

DB: flat.adv.deformsbr.32.3l4.grad.T1.001422.2d.hdf5  
Cycle: 1422 Time: 8.8875



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

# Advection Test: Moving Vortices



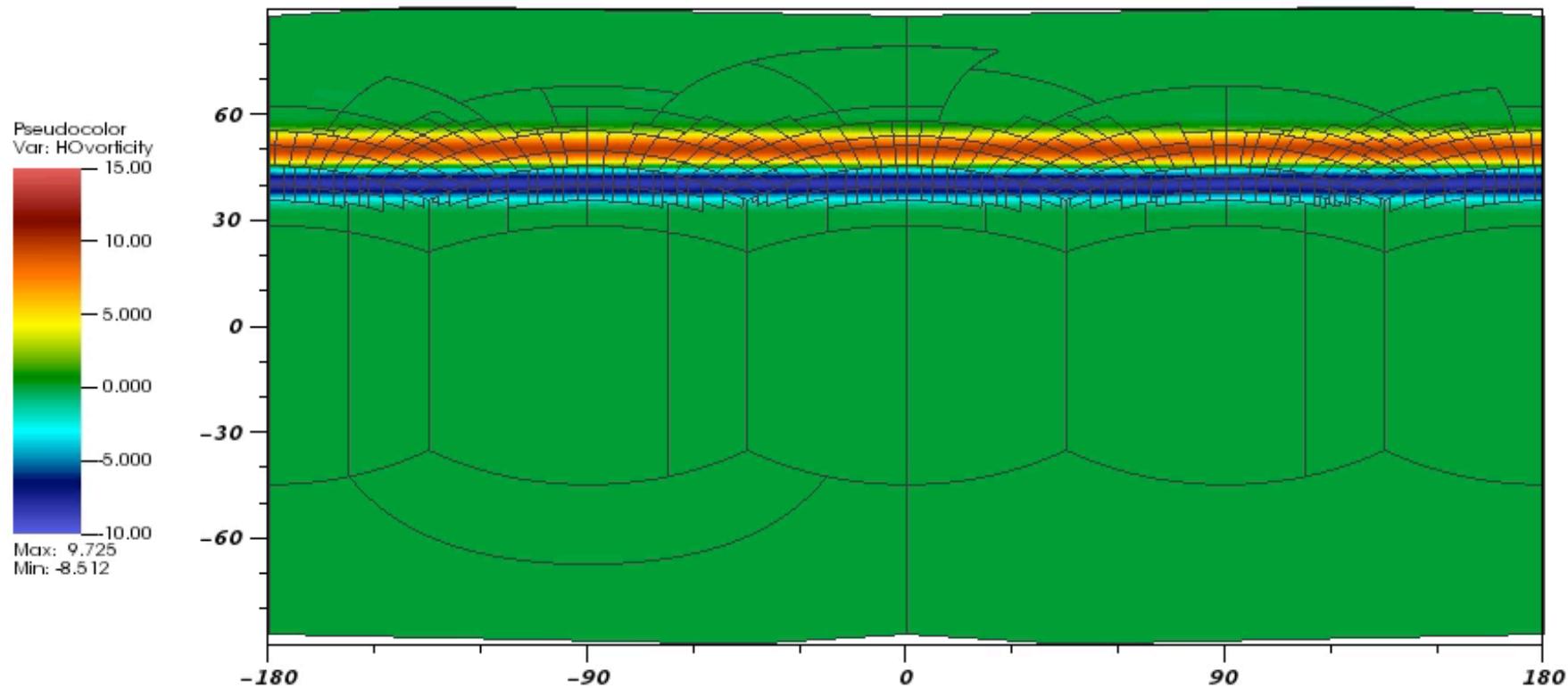
EARTH SCIENCES  
DIVISION



# Shallow Water Test: Barotropic Instability

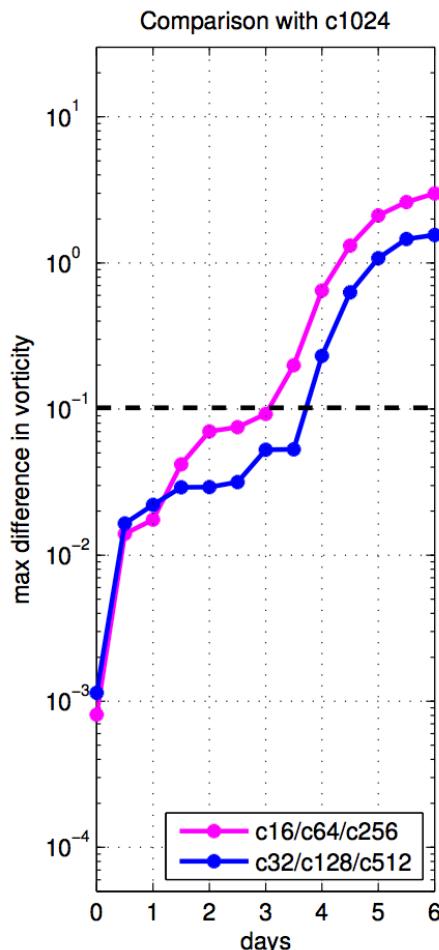
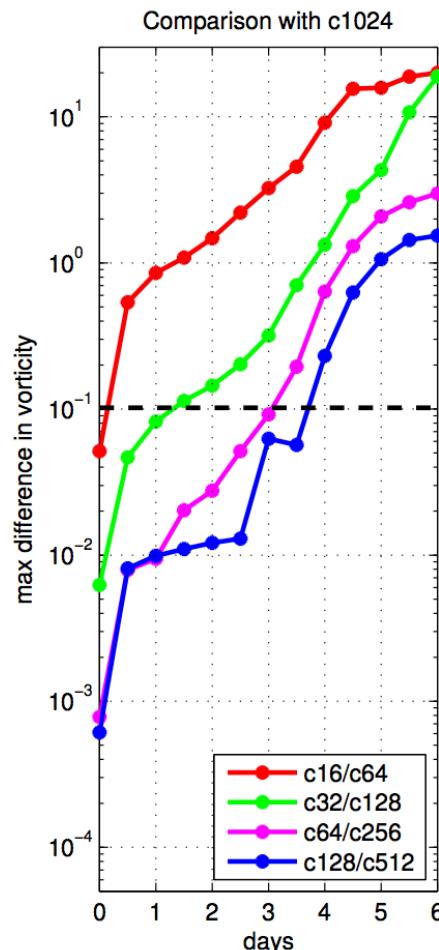
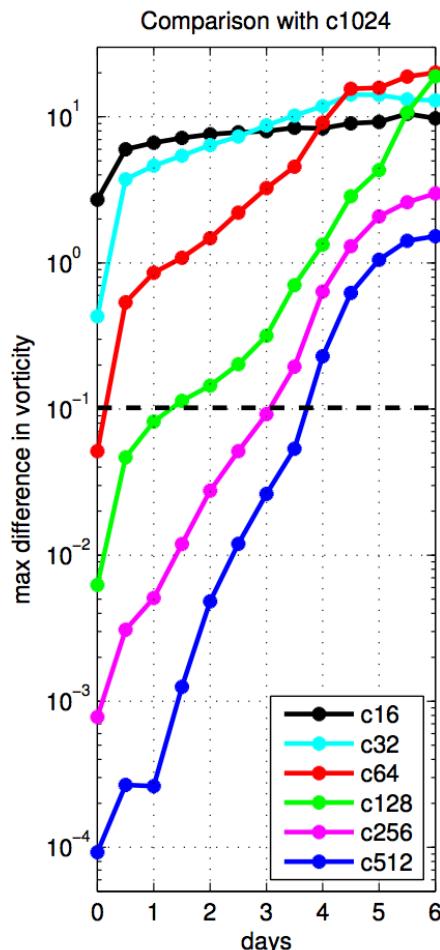
- Galewsky et al. 2004, barotropic instability test

DB: flat.jof.swe.barotropicinstability.32.314.T1.000320.2d.hdf5  
Cycle: 320 Time: 2



# Shallow Water Test: Barotropic Instability

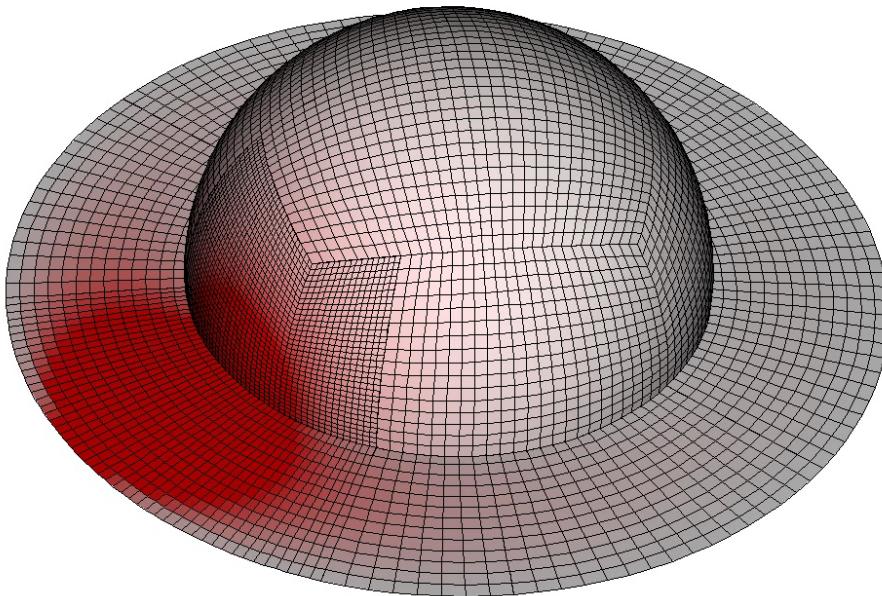
- Plots of maximum difference in relative vorticity (in units of day<sup>-1</sup>)
- Results from *McCorquodale, et al. 2015*



# Nonorographic gravity waves

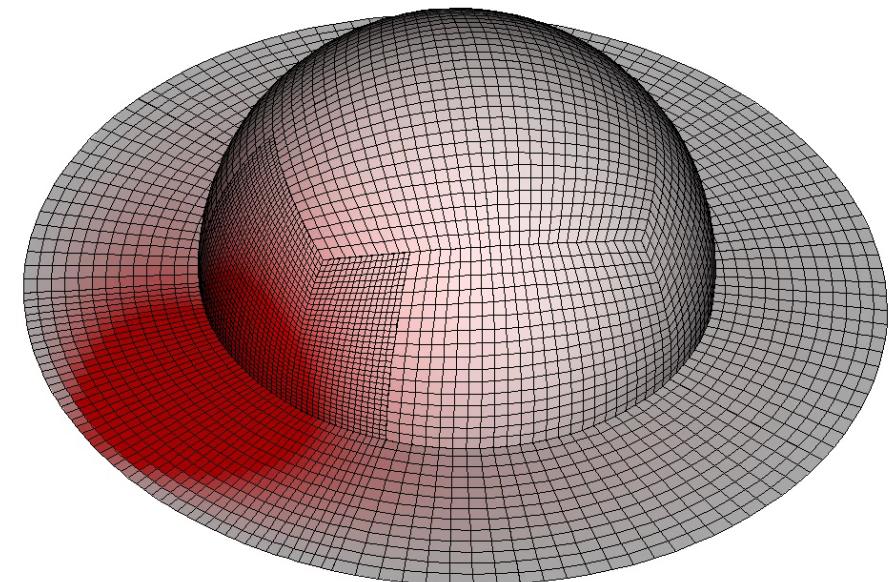
DCMIP-2012 Test 3-1: Potential Temp.  
perturbation at equator.

DB: climate.gravity.000000.3d.hdf5  
Cycle: 0 Time:0



Potential Temperature perturbation

DB: climate.gravity.000000.3d.hdf5  
Cycle: 0 Time:0



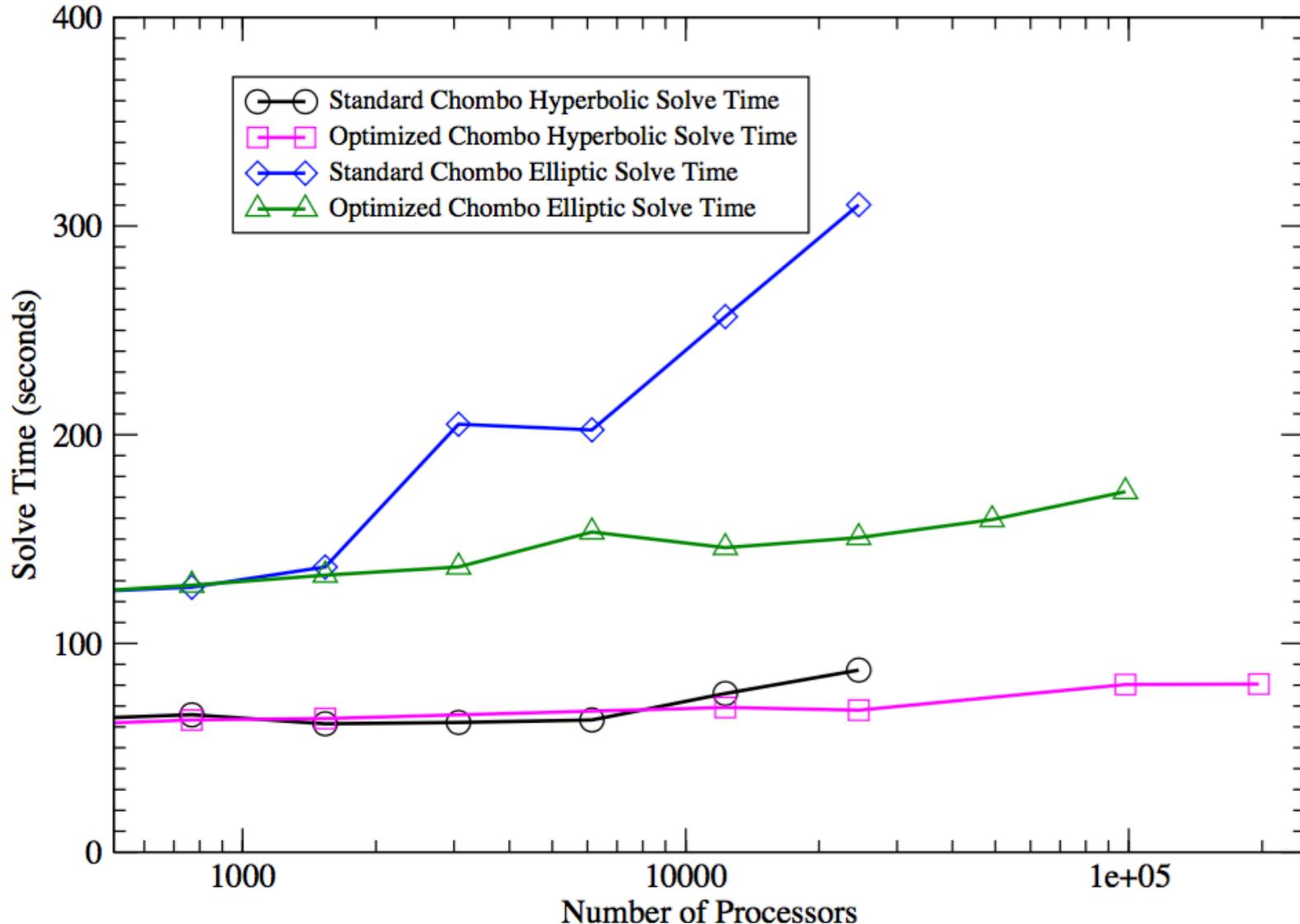
Pressure perturbation

- 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!

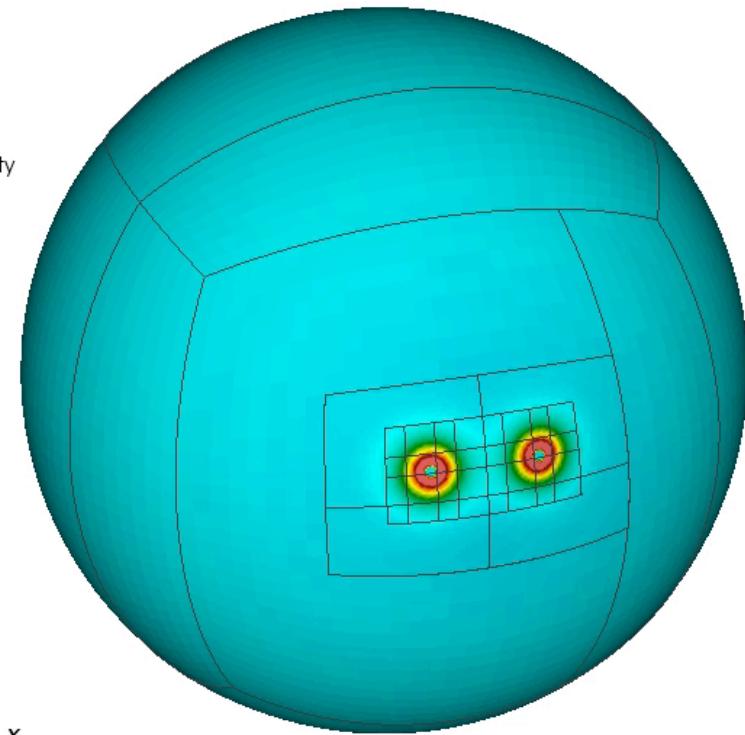
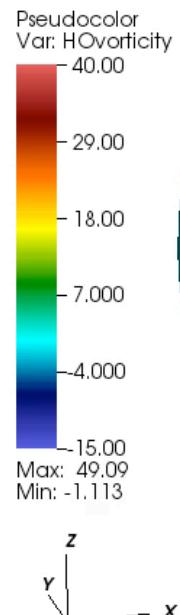
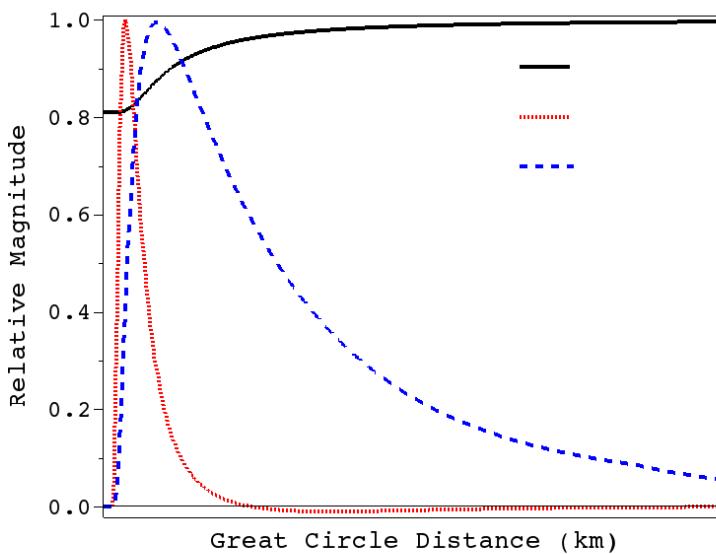
# Extra Slides

# Chombo-AMR Scaling



# Shallow Water Test: Binary Vortices- Merging Case

DB: jof.swe.symvortices.32.3I4.T66.000000.2d.hdf5  
Cycle: 0 Time:0



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