# Assessments of the Chombo AMR Model in Shallow Water Mode

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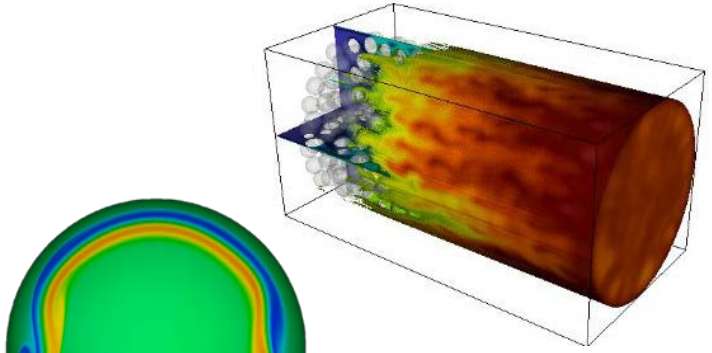
With: LBNL ANAG (P. McCorquodale, H. Johansen, P. Collela), P. Ullrich (UC Davis)

# LBNL ANAG and Chombo

***Applied Numerical Algorithms Group (ANAG)*** at LBNL, Phil Colella, group lead. http://crd.lbl.gov/anag

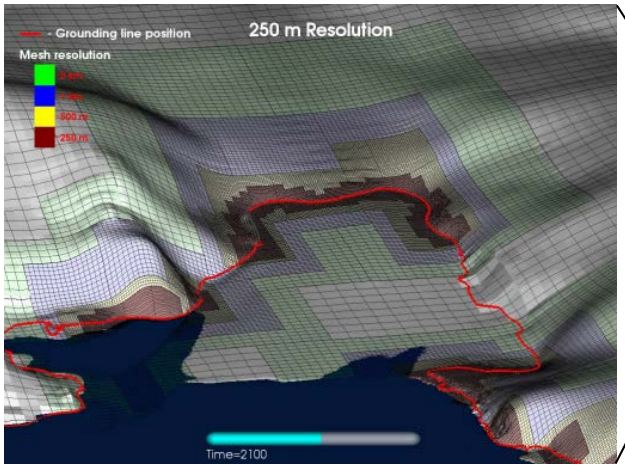
*with collaborators P. McCorquodale, H. Johansen*

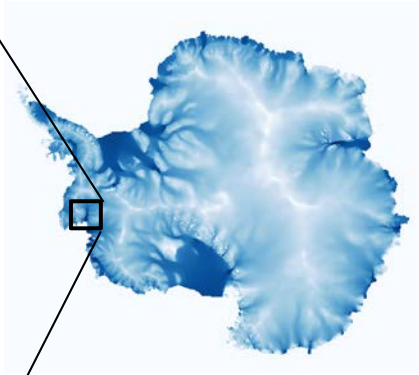


***Chombo***: Open Source Software Toolkit for Structured-Grid Applications in C++/Fortran. http://chombo.lbl.gov

Framework / algorithm features:

- High-order, finite-volume methods, space-time adaptive mesh refinement (AMR)
- Multiscale models for complex fluids, phase space, multi-physics, semi-implicit
- Fast solvers minimize communication, memory access – scales to (200k+ processors) with low-level details hidden.



*"Makes the easy things harder, but impossible things possible."*

# Chombo AMR Dycore

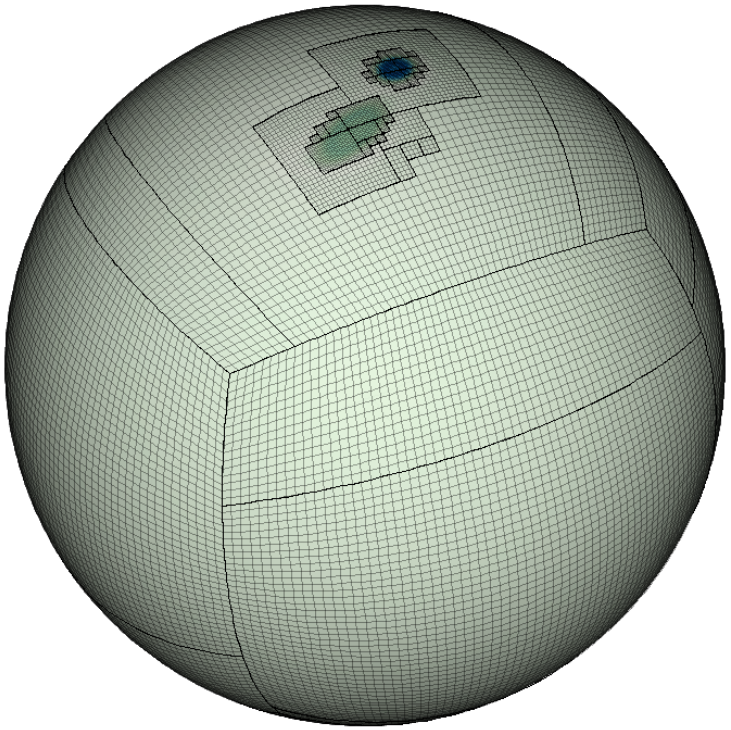
- High-order finite-volume approach
- Uses multi-block grids on an equiangular cubed sphere
- Classical 4th order Runge-Kutta temporal discretization
- Adaptive mesh refinement through a hierarchy of nest meshes

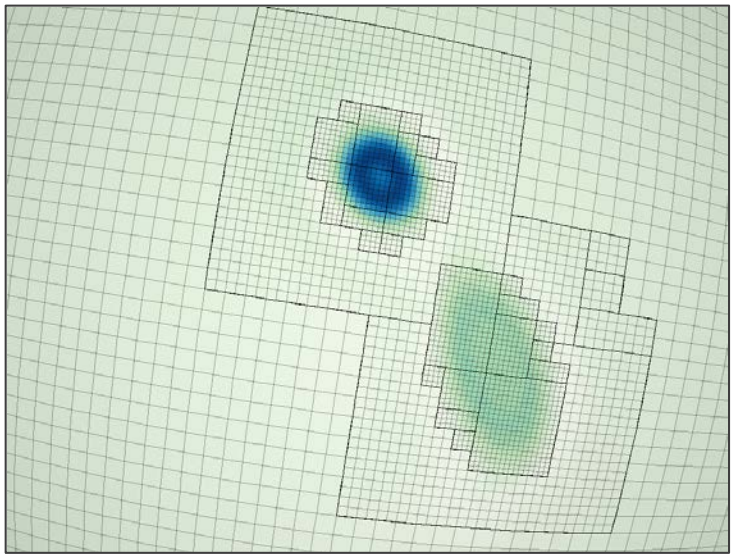
$$\frac{\partial}{\partial t}(J\mathbf{U}) + \nabla \cdot (J\vec{\mathbf{F}}) = J\mathbf{\Psi},$$

$$\mathbf{U} = \begin{pmatrix} h \\ hu^{\alpha} \\ hu^{\beta} \end{pmatrix}, \ \mathbf{F}^{k} = \begin{pmatrix} hu^{k} \\ \mathcal{T}^{\alpha k} \\ \mathcal{T}^{\beta k} \end{pmatrix}, \ \mathbf{\Psi} = \begin{pmatrix} 0 \\ \mathbf{\Psi}^{\alpha}_{\mathrm{M}} + \mathbf{\Psi}^{\alpha}_{\mathrm{B}} + \mathbf{\Psi}^{\alpha}_{\mathrm{C}} \\ \mathbf{\Psi}^{\beta}_{\mathrm{M}} + \mathbf{\Psi}^{\beta}_{\mathrm{B}} + \mathbf{\Psi}^{\beta}_{\mathrm{C}} \end{pmatrix}.$$

$$\mathcal{T}^{ki} = hu^{k}u^{i} + g^{ki}\tfrac{1}{2}Gh^{2}$$

# Chombo AMR Dycore

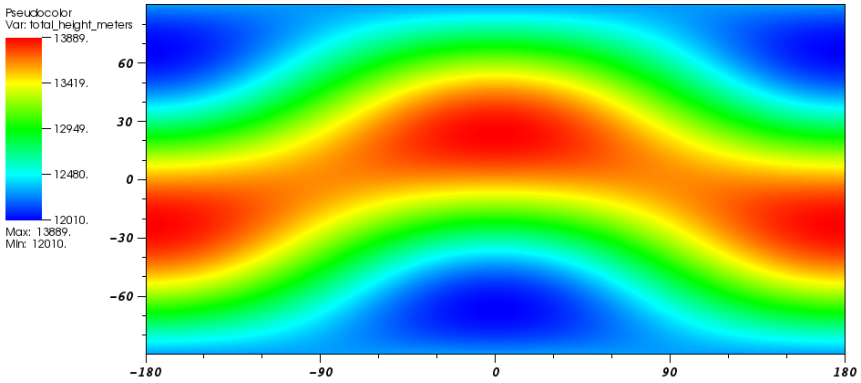




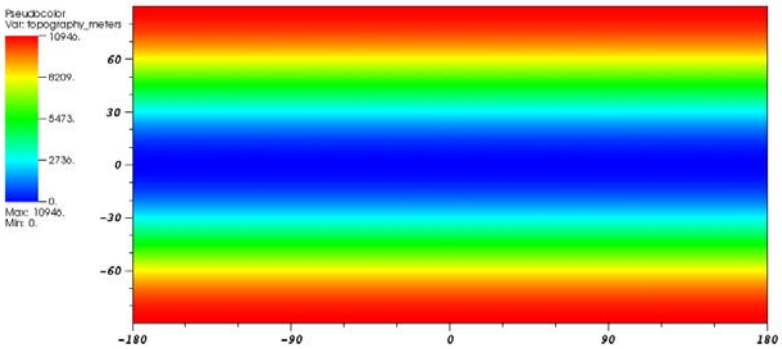
# SW Test Case: Unsteady Solid Body Rotation

- Proposed in Läuter 2004
- An unsteady solid body rotation forced by orography
- Fairly artificial, but has analytic solution to the SWE
- Unsteadiness attractive for testing AMR

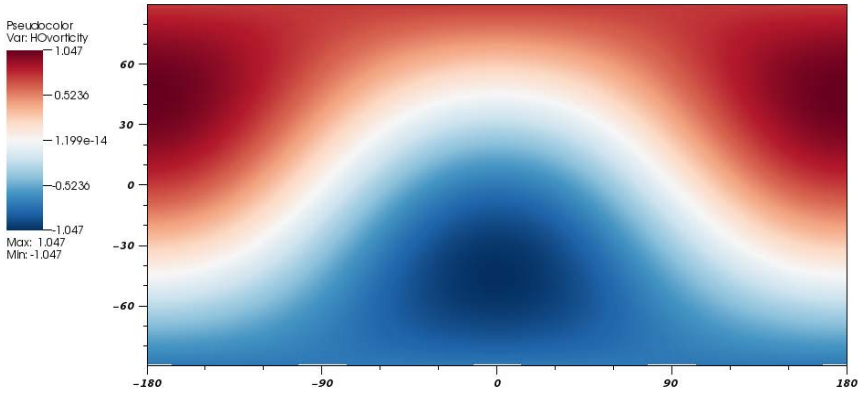
Height




Orography

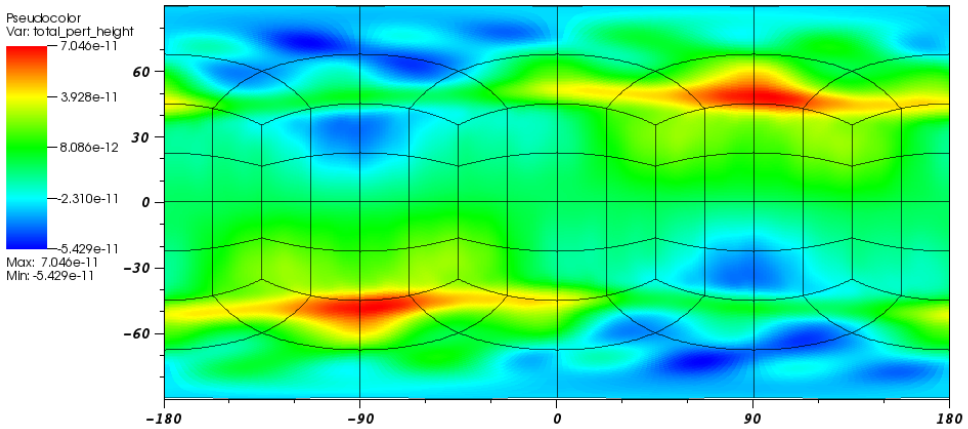



Vorticity

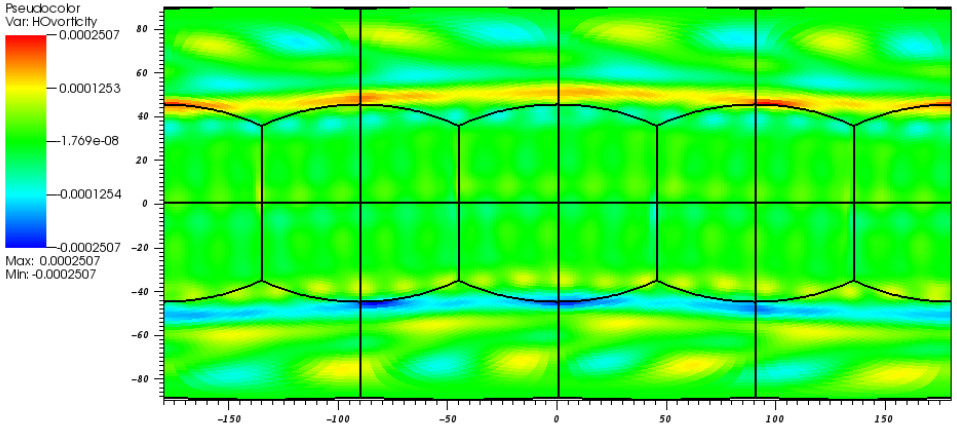


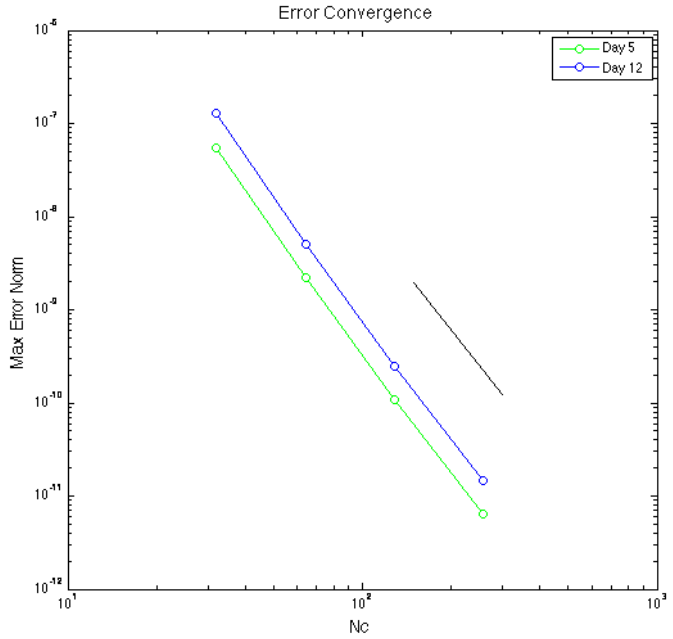
# SW Test Case: Unsteady Solid Body Rotation

## Height




## Vorticity



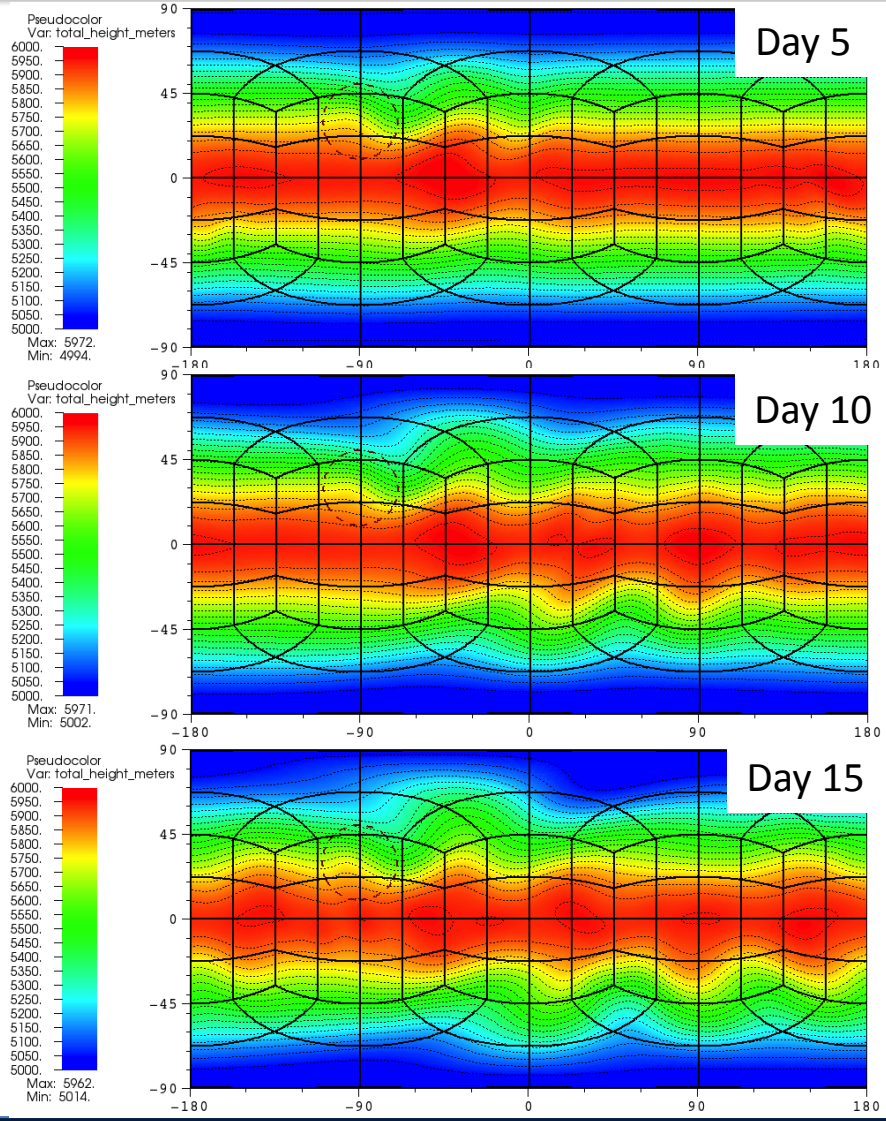
# SW Test Case: Flow over isolated Mountain

- Williamson et al., 1992 test case 5
- Modified version with mountain given by a $C^3$ cosine hill:

$$z_s = \frac{z_0}{4}\left[1+\cos\left(\frac{\pi r}{R}\right)\right]^2$$

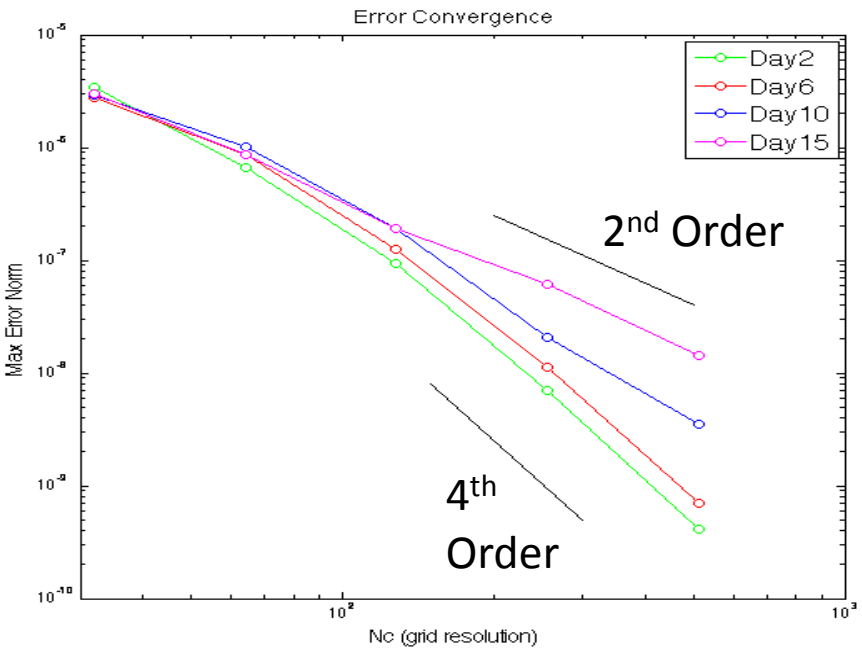
$$r^2 = \min\{R^2, (\lambda-\lambda_c)^2+(\phi-\phi_c)^2\}$$

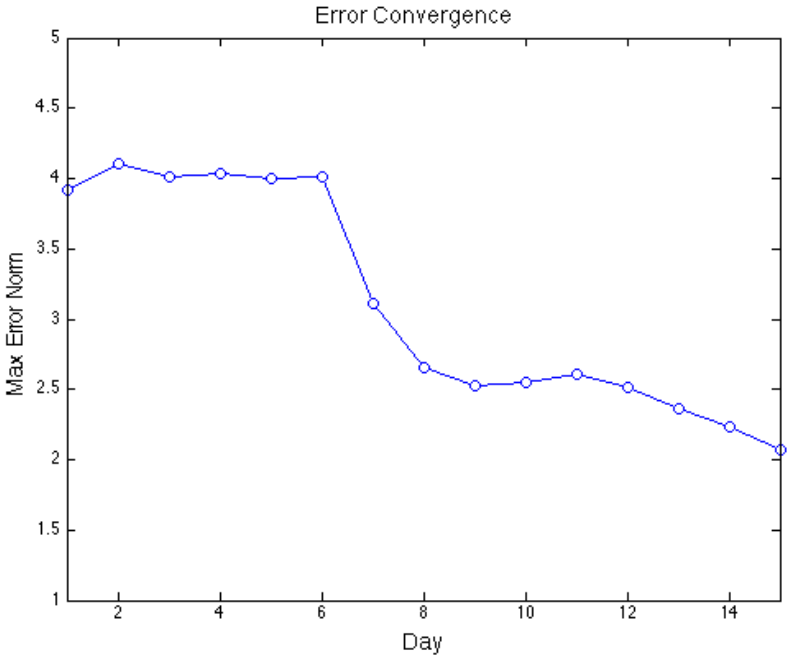
- 15 day runs with uniform refinement



# SW Test Case: Flow over isolated Mountain

## Error Comparison and Convergence Rates

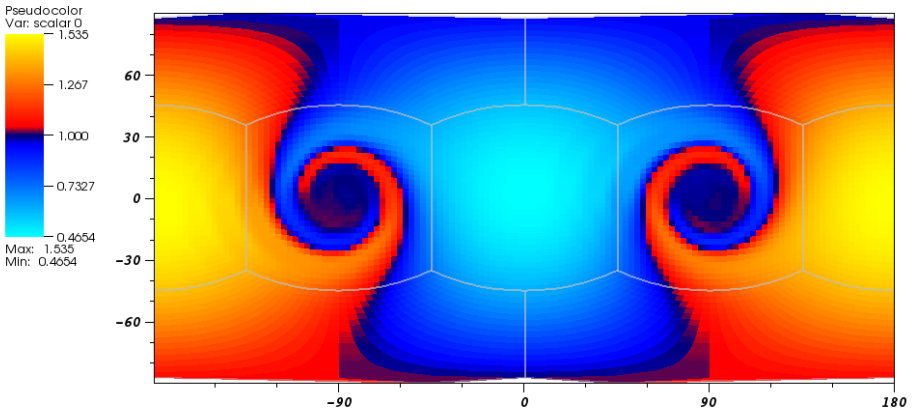


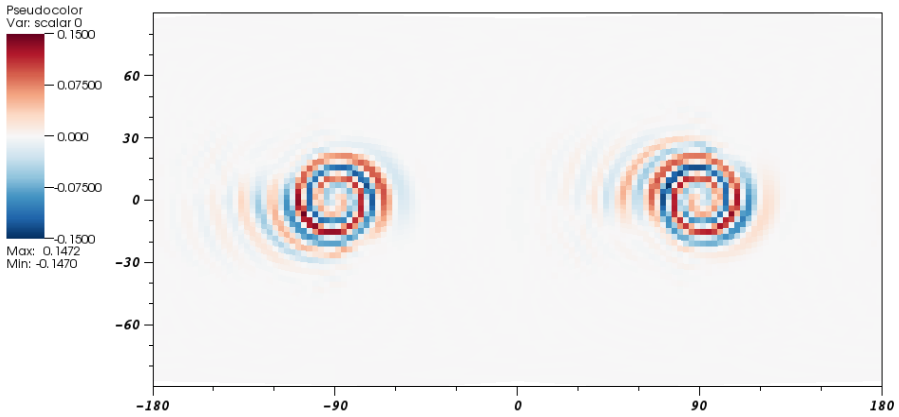



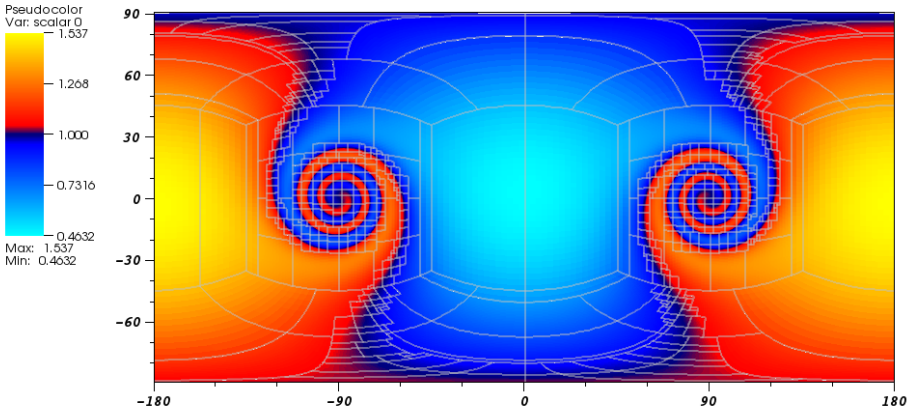
# Advection Test Case: Moving Vortices

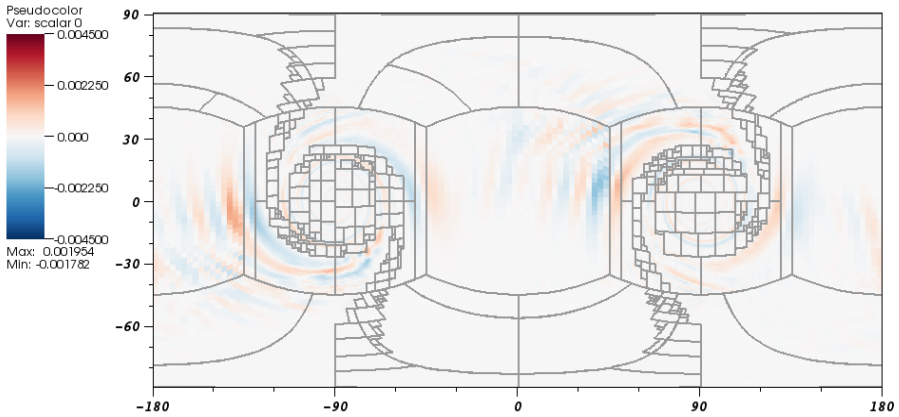
- Proposed by Nair, Jablonowski 2007
- Combines solid-body rotation and deformational flow
- Initially smooth transported scalar develops strong gradients
- Analytic solution known in time

# Advection Test Case: Moving Vortices



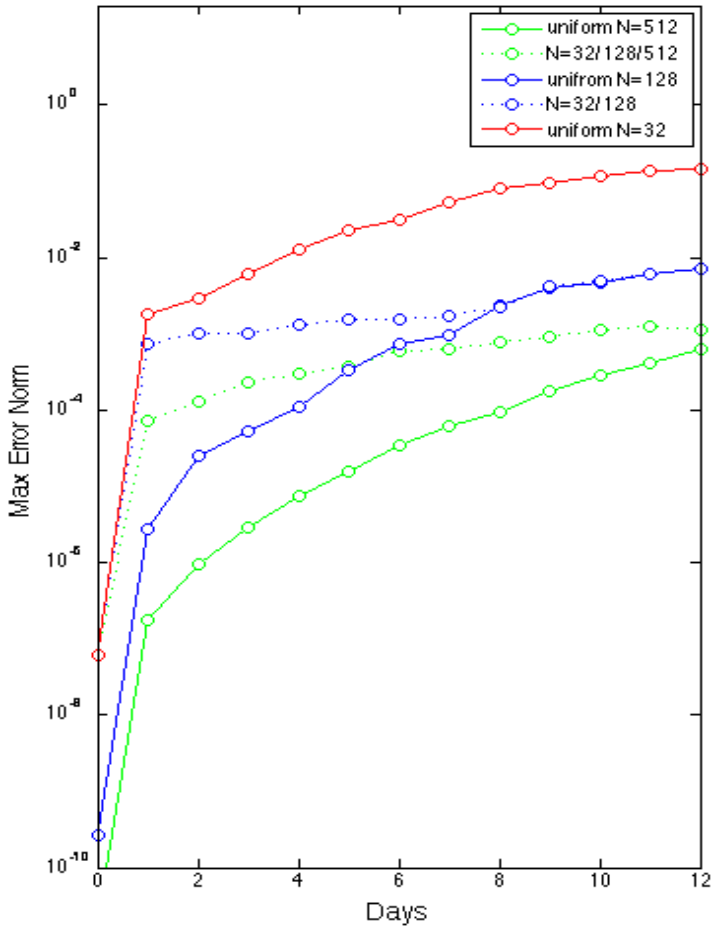



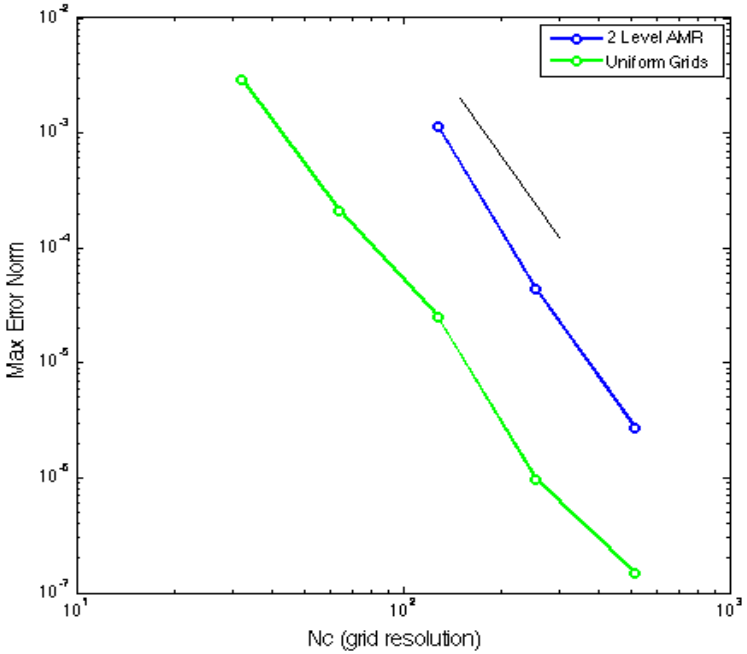



# Advection Test Case: Moving Vortices

Max Error

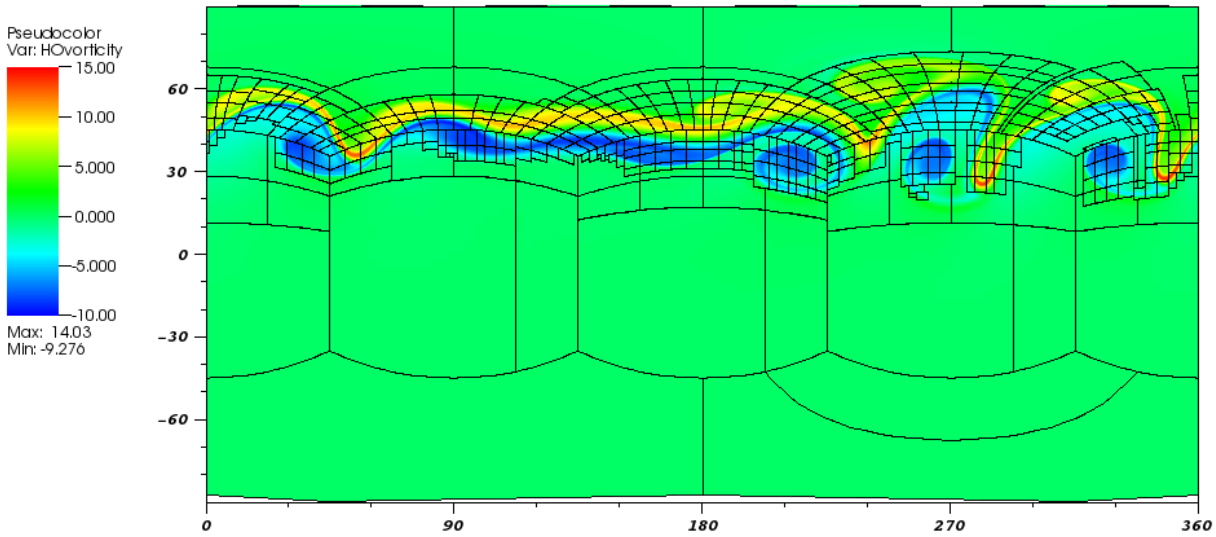



Error Convergence



# SW Test Case: Barotropic Instability

- Galewsky (2004) test case
- Consist of a zonal jet with compact support at latitude of 45°.
- Small height perturbation on jet leads to development of instability
- Tagged based on absolute vorticity

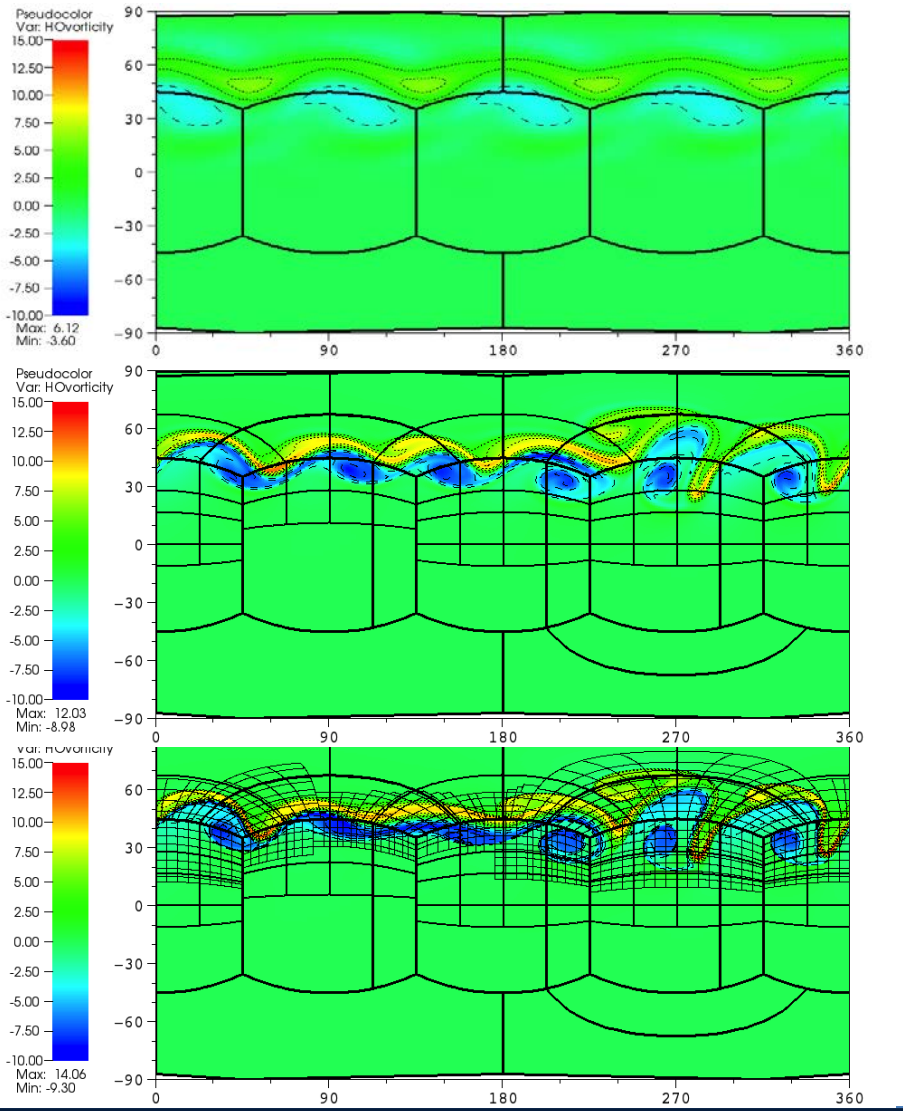


# SW Test Case: Barotropic Instability

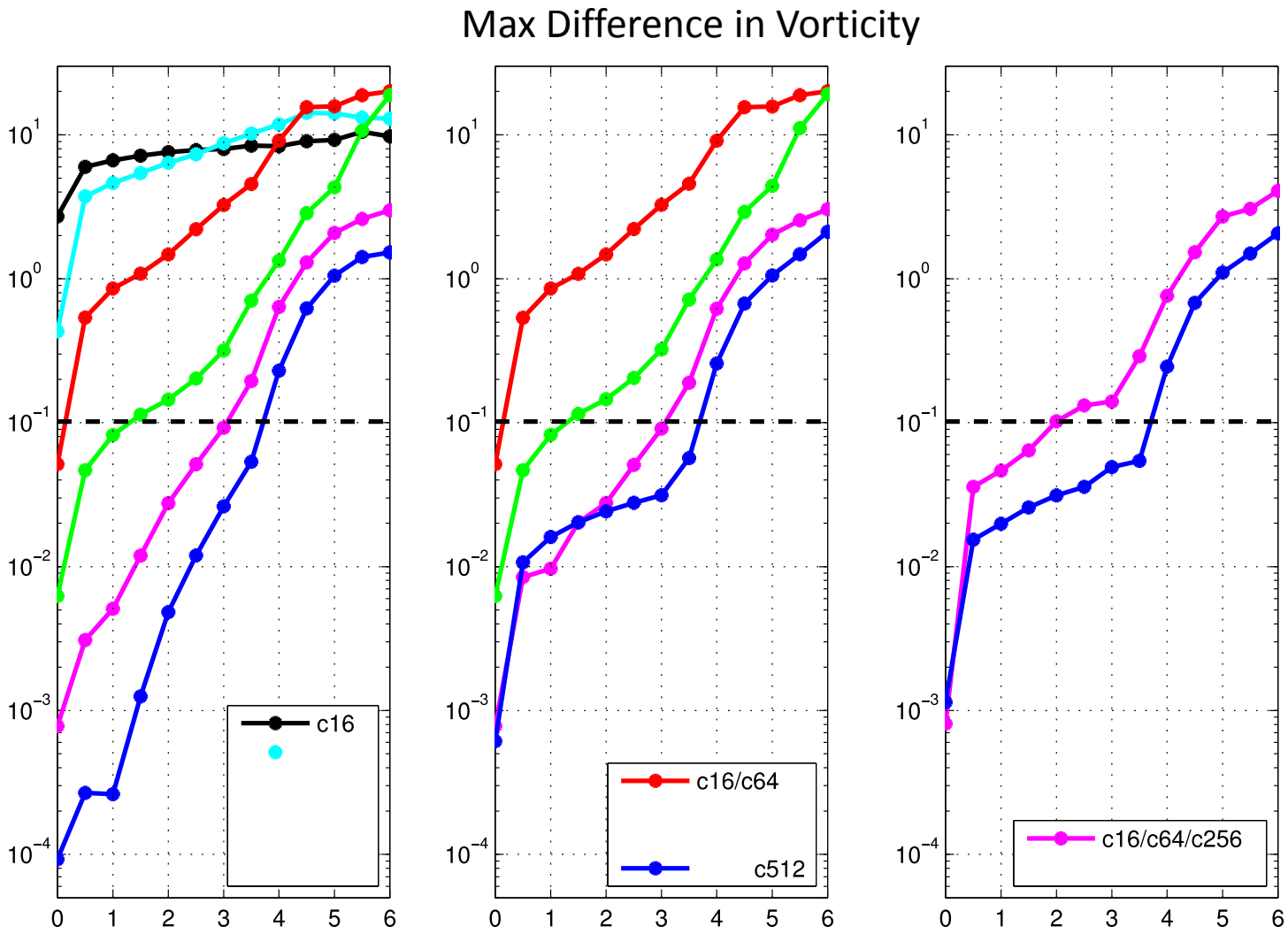
1 Level: c32

2 Levels: c32/c128

3 Levels: c32/c128/c512



# SW Test Case: Barotropic Instability



# Conclusions

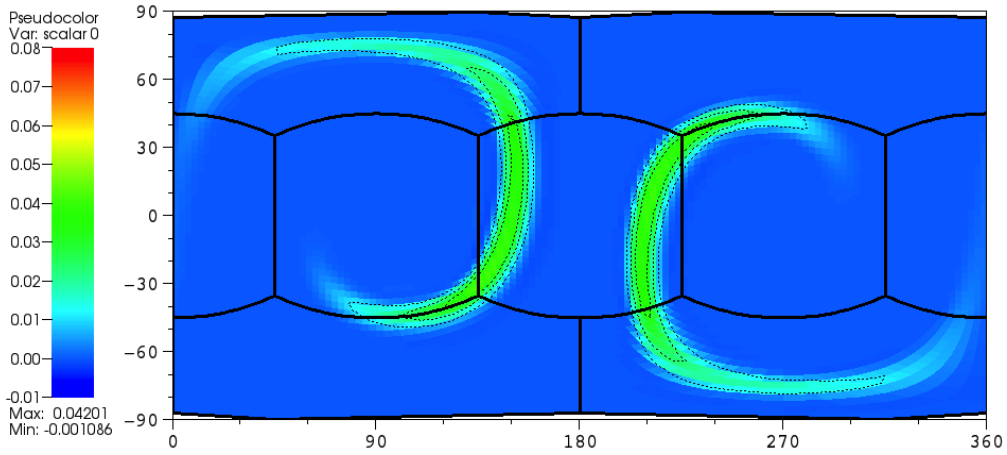
- It works
- Converging to $4^{th}$ order
- No visible artifacts from the AMR
- Comparable accuracy between AMR and uniform grid

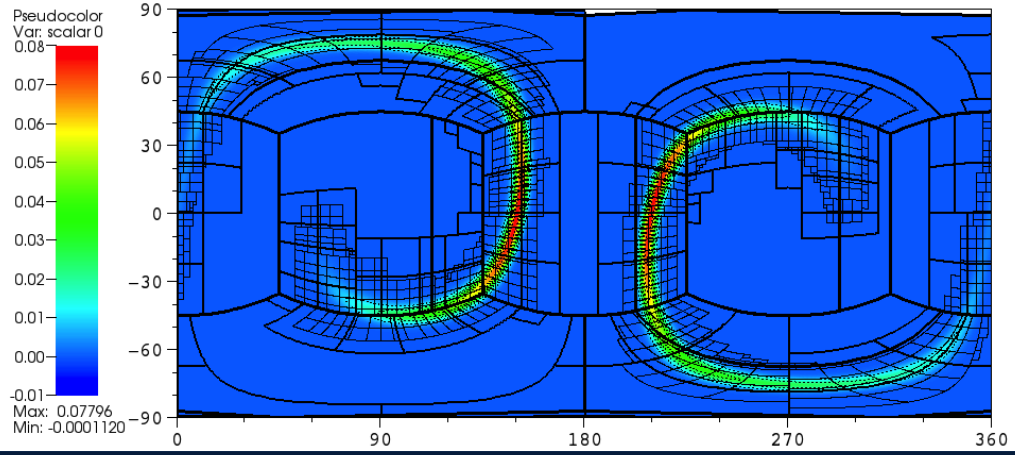
# AMR SWE – Future Work

- Currently verifying 3D non-hydrostatic dycore
  - Vertical implicit for aspect ratios up to 1000:1
  - Verifying stability: linearized gas dynamics tests
  - Aquaplanet adiabatic tests next
- Coupling with CESM column physics
  - With LBNL ESD: W. Collins, J. Benedict, J. Johnson
  - AMR to track TC's, atmospheric rivers, ETC's
  - Will use space-time resolution (< 2.5 km/10 s) to test scale-dependence of column physics

# Advection Test Case: Deformational Flow

- Advection horizontal tracer transport from Nair and Lauritzen 2010
- 2 Gaussian Hills



# Advection Test Case: Deformational Flow

## Error at final time