Development of a Multiscale Global Climate Model with Adaptive Mesh Refinement

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Introduction / Motivation

We are developing an adaptive atmospheric dynamical core ("dycore") in the Chombo framework (chombo.lbl.gov) for high-accuracy global climate simulations:

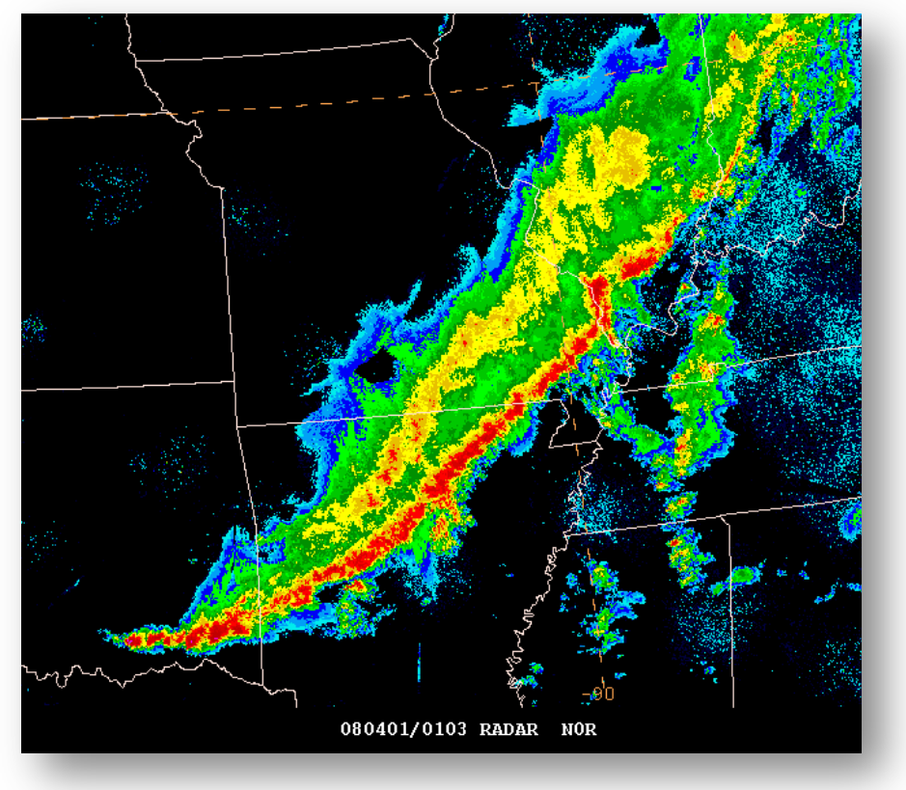

Fig 1: Radar image of a squall line over central US

Chombo is a high-order massively scalable finite-volume framework for robust and accurate solution of partial differential equations in arbitrary geometry. Chombo also provides a block-adaptive adaptive mesh refinement (AMR) capability to allow feature isolation and tracking. Scientific applications include:

- Greater resolution of dynamic features (squall lines, atmospheric rivers)
- Regional weather phenomena (tropical cyclones, coastal climate)
- Grid refinement studies for new physics (cloud parameterizations)
- Evaluation of time discretization errors from 1D operator splitting ("column physics")

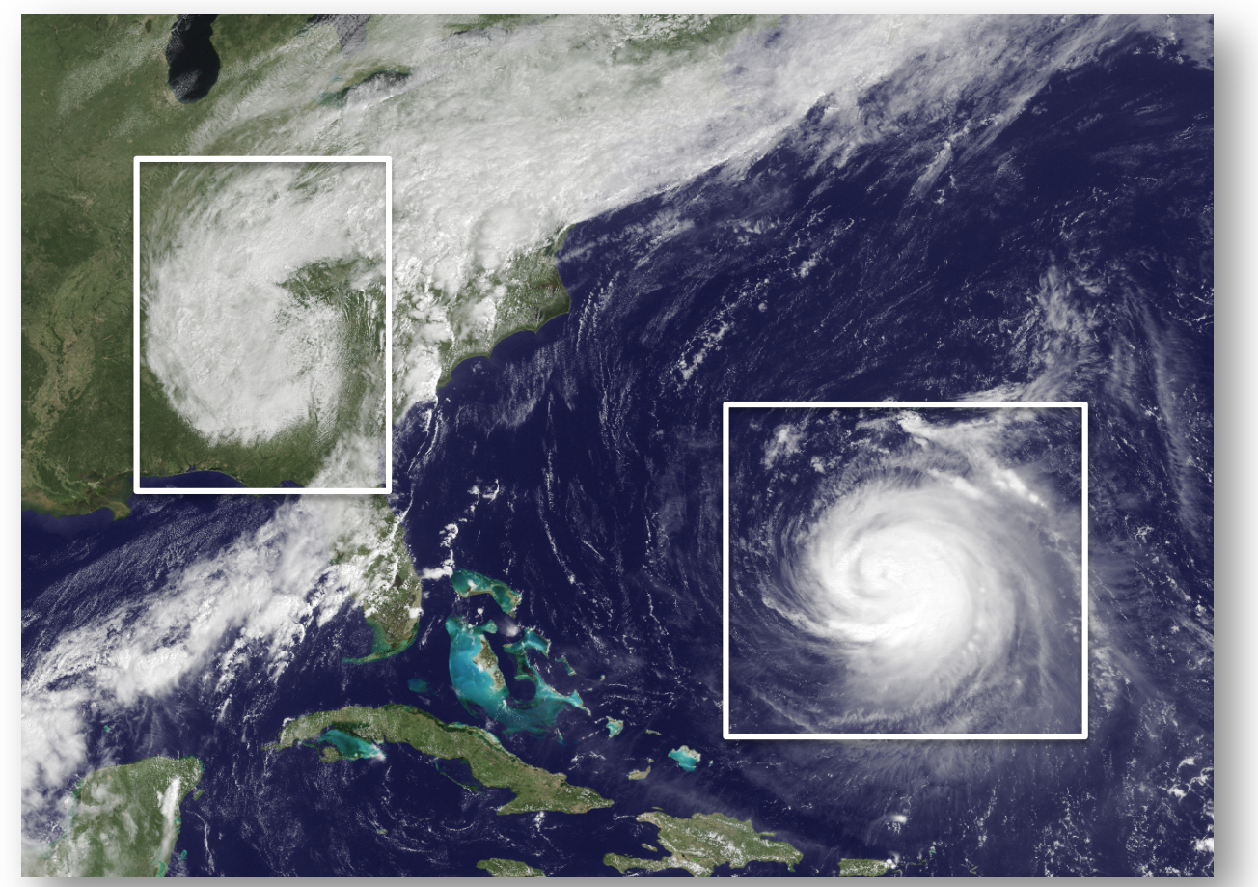

Fig 2: Tropical cyclones Lee and Katia, 6 September 2011, and associated tracking boxes.

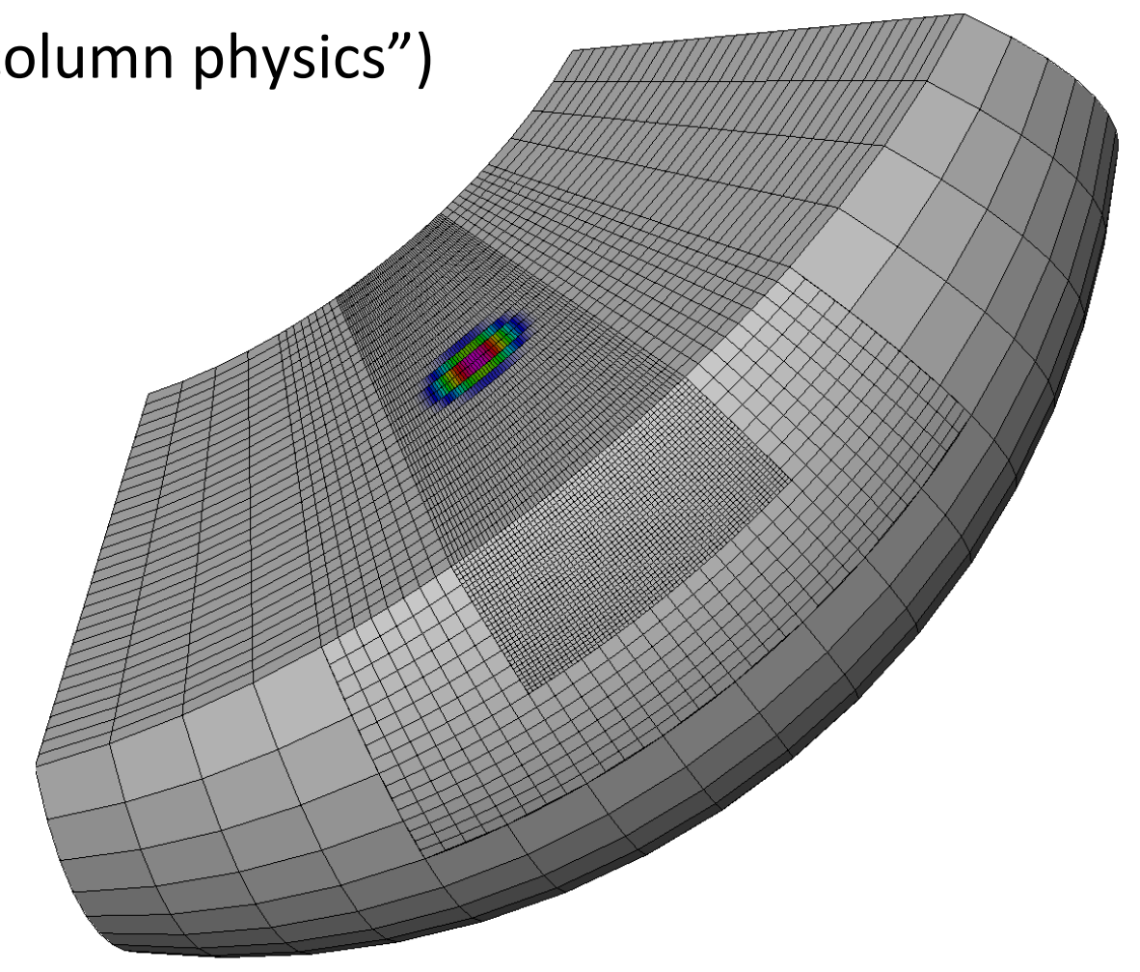

Fig 3: AMR with 16:1 refinement ratio between coarsest and finest levels

Non-Hydrostatic Equations and Grids

We follow the approach in [UJ2012] , which discretizes spherical shells (atmospheric levels) using:

- "Thin atmosphere" approximation neglects radial dependence of grid metrics.
- Equiangular coordinates in horizontal directions (α,β) on 6 panels closely related to gnomonic (great circle) coords.
- Stretched vertical mapping $r(\xi)$ for boundary layer refinement in radial direction.
- Implicit-explicit time integration for treatment of vertical acoustic modes.

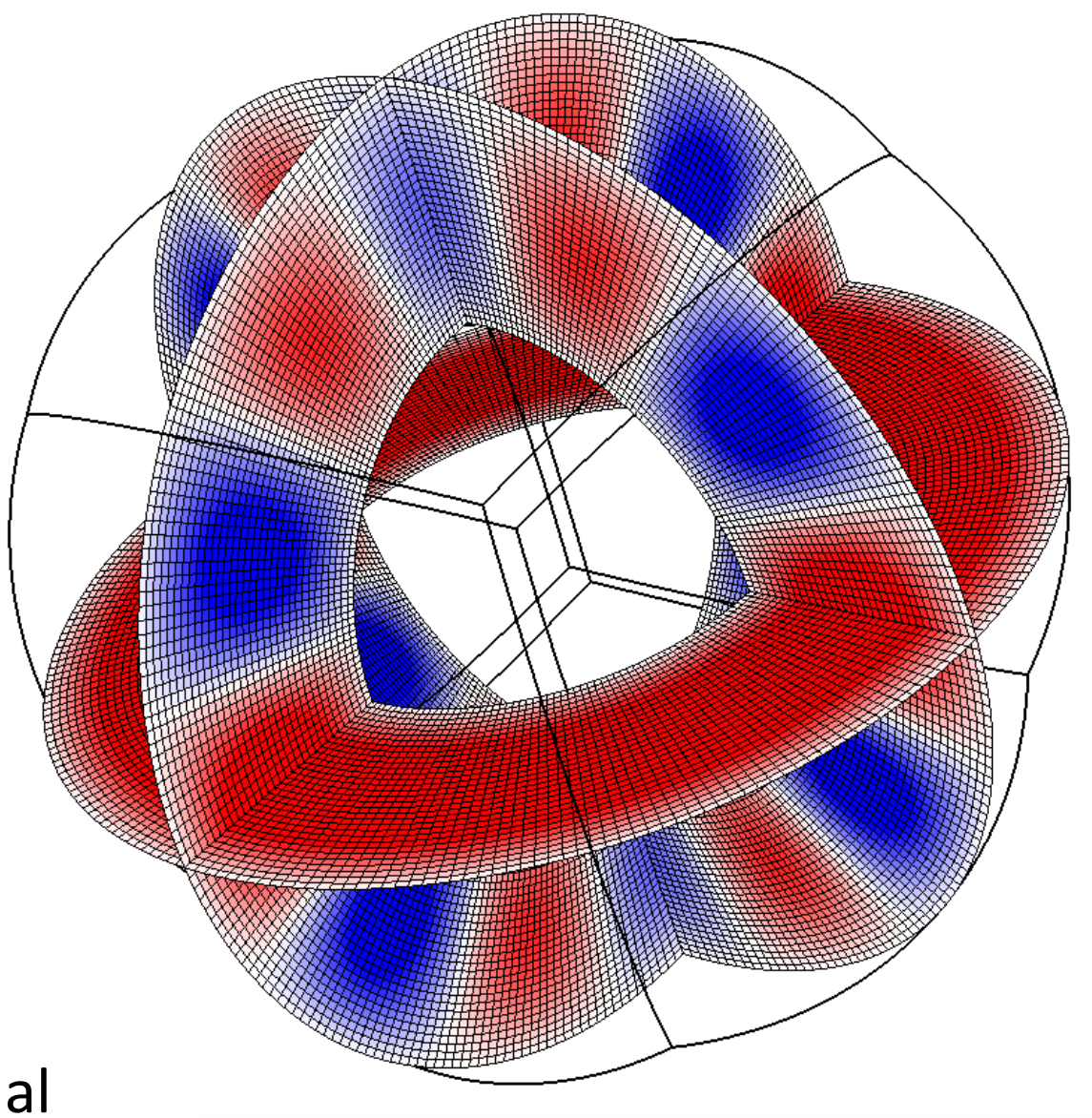

Fig 5: Cut-away of cubed sphere with Hadley cell vertical velocity

Fig 4: The quasi-uniform cubed-sphere grid is used to discretize the spherical surface. A refinement patch over California allows for better resolution of California climate at reduced cost.

At panel boundaries, the mapping is continuous but not smooth, and additional work is required:

- 4th-order least squares interpolation of conserved variables between panels
- *Orthonormalization* of vector quantities at panel boundaries.

Fig 6: To capture topographic variations, terrain-following coordinates are used. *Figure courtesy David Hall, UC Boulder.*

Cross-Validation

To ensure correct performance of the Chombo code, the model is being continuously cross-validated against the Tempest non-hydrostatic spectral element atmospheric modeling framework [U2014]. This framework uses a spectral element discretization in the horizontal direction and finite element vertical discretization for solving the non-hydrostatic equations of motion.

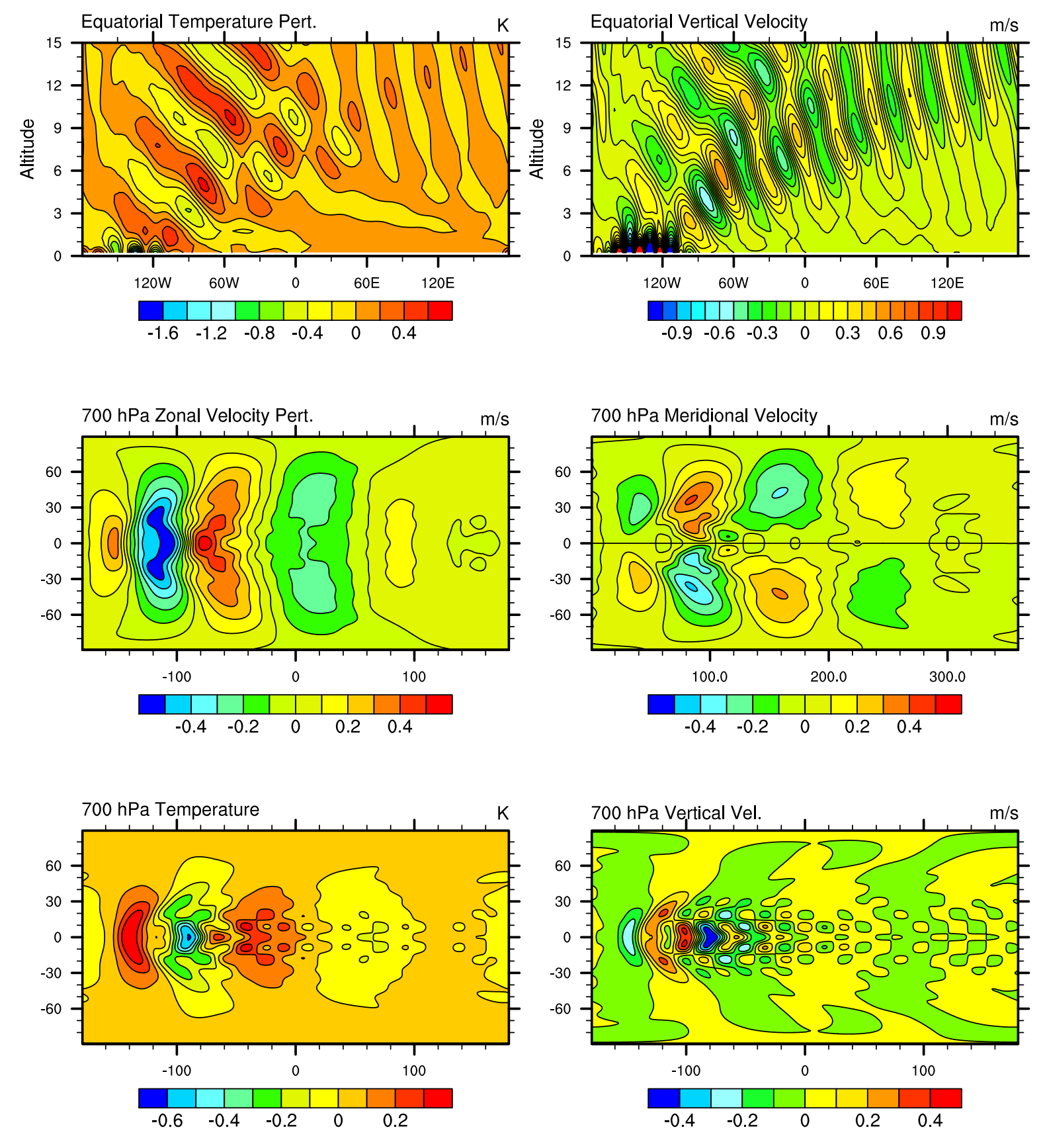

Fig 7: A mountain wave response to a wavelet-like mountain on a reduced Earth (non-hydrostatic scales) is simulated by the Tempest model.

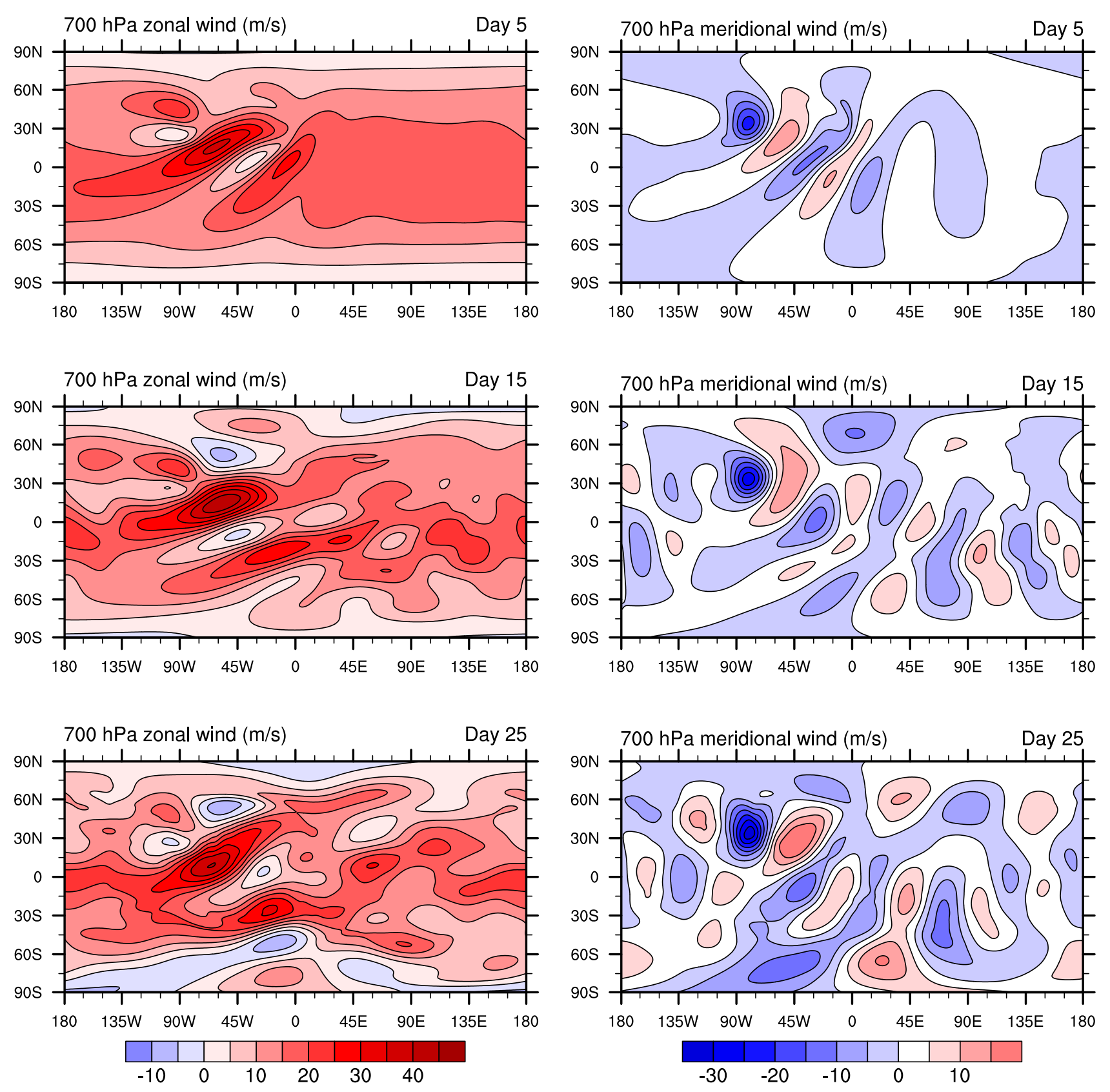

Fig 8: A wave response to underlying topography is simulated in the Tempest model. Here zonal wind velocity and meridional wind velocity is shown.

AMR: Shallow-Water on the Sphere

The shallow-water equations on the sphere are an important test bed for evaluating horizontal dynamics in a modeling system.

Adaptive mesh refinement has been successfully employed on a suite of idealized test problems to verify accuracy and robustness of the algorithm, including tracer transport, geostrophically balanced flow, mountain-induced Rossby waves and barotropic instability. All results have been shown to exhibit 4th-order scalability [MUJC2014].

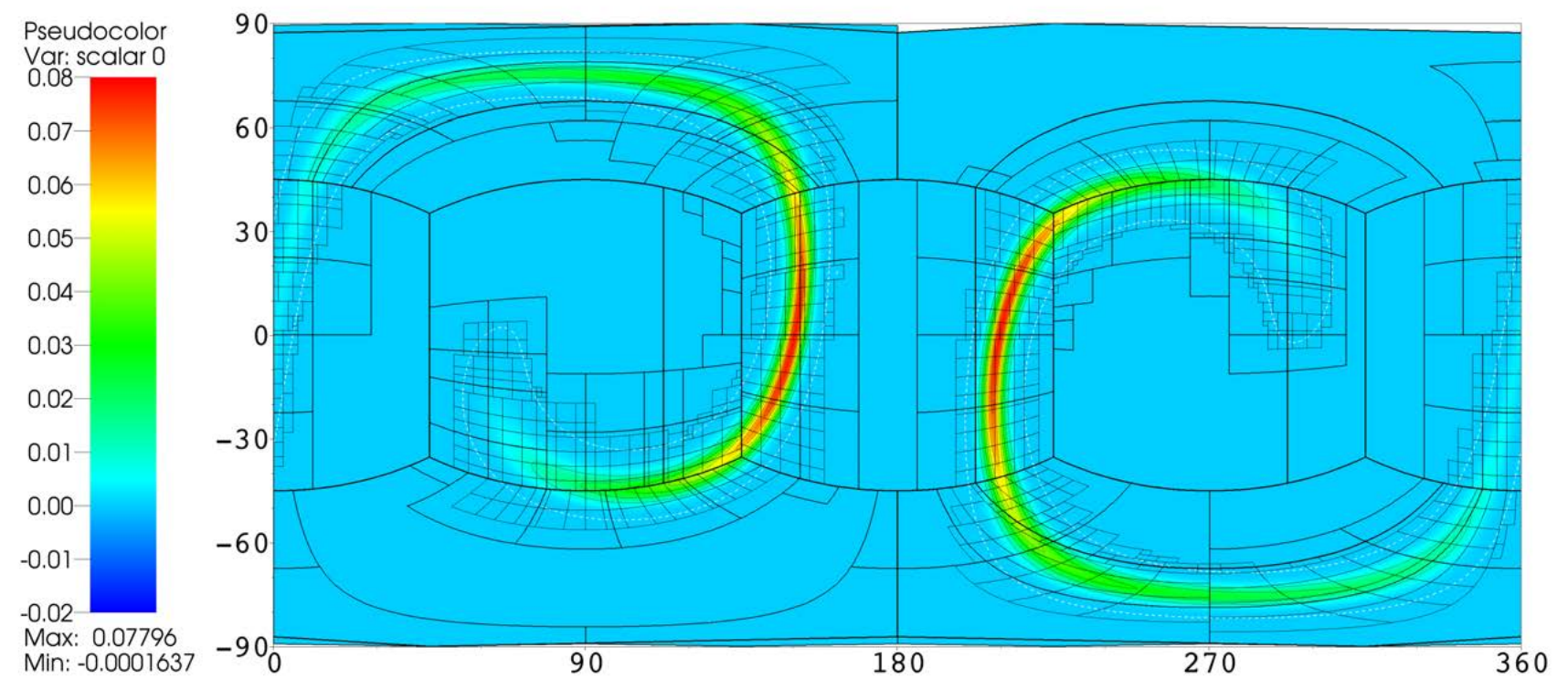

Fig 9: Lat-lon plot of global tracer transport in a deformational flow with strong filamentation. The adaptive methodology effectively tracks tracer concentrations to avoid spurious numerical diffusion.

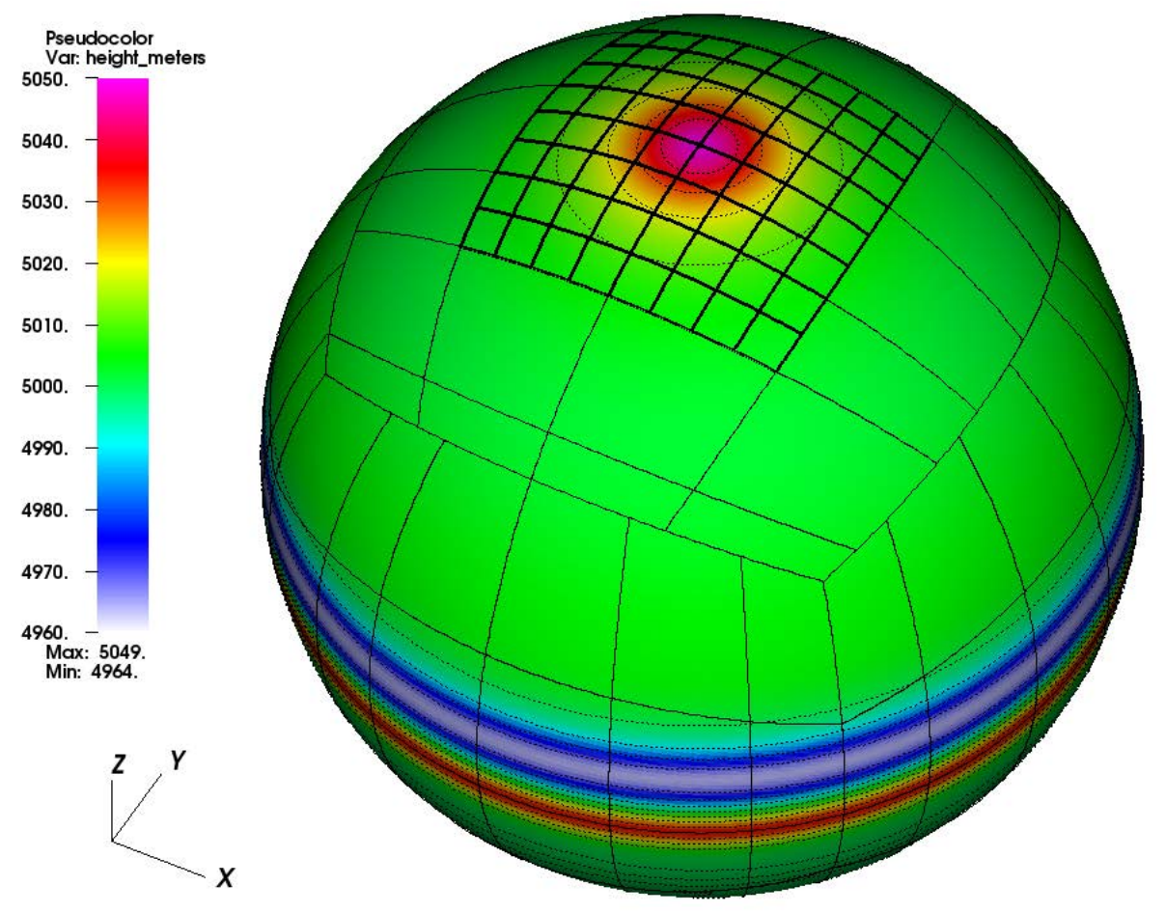

Fig 10: A gravity wave passes smoothly through a refinement boundary towards the equator without any obvious grid artifacts.

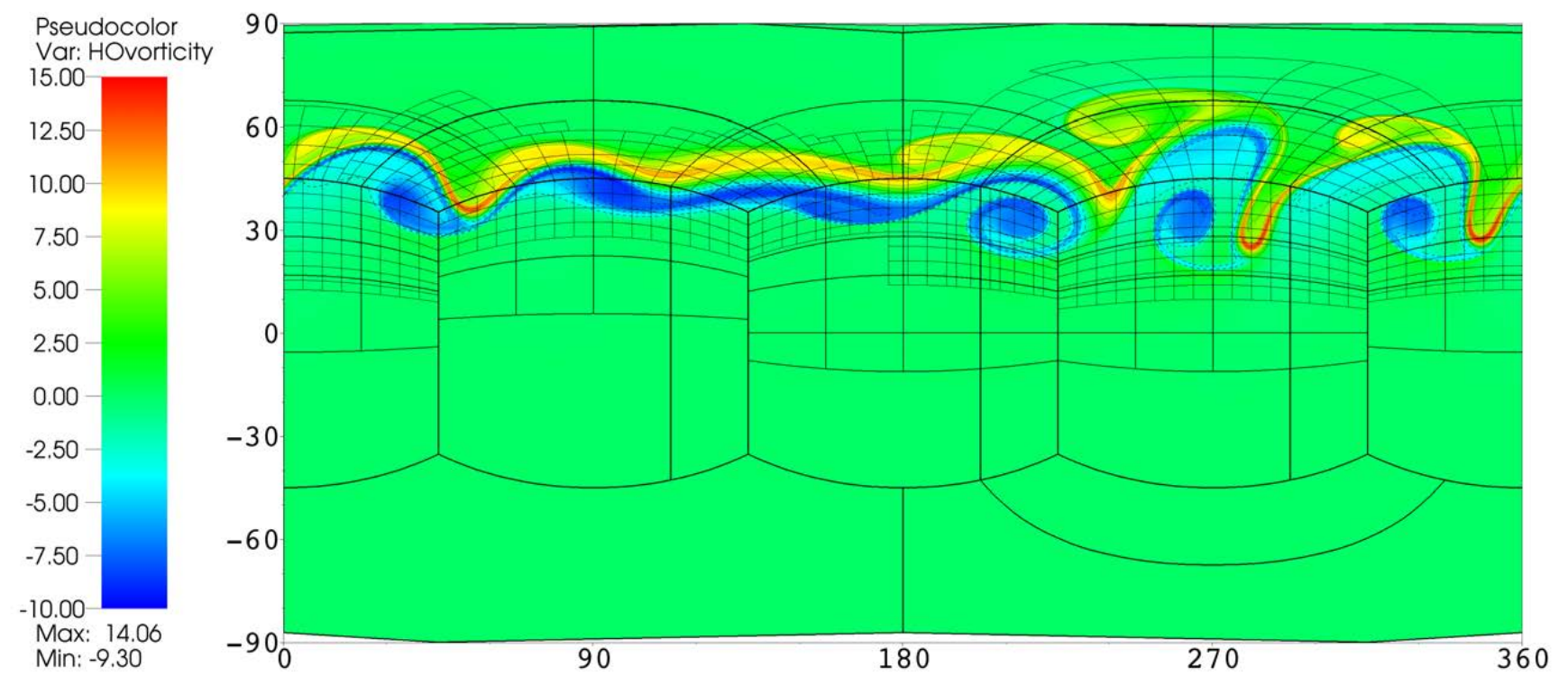

Fig 11: Lat-lon plot of relative vorticity for an evolving barotropic instability, demonstrating accurate resolution of vorticity filaments.

AMR: Non-Hydrostatic Flow on the Sphere

Testing is ongoing on the development of AMR for 3D non-hydrostatic dynamics. Different grids can be utilized for different tracer species, and for dynamical features such as vorticity. A number of outstanding problems are undergoing active research, including how to dynamically refine without generating spurious gravity waves and how to conserve mass when the underlying topography is modified by the underlying topography.

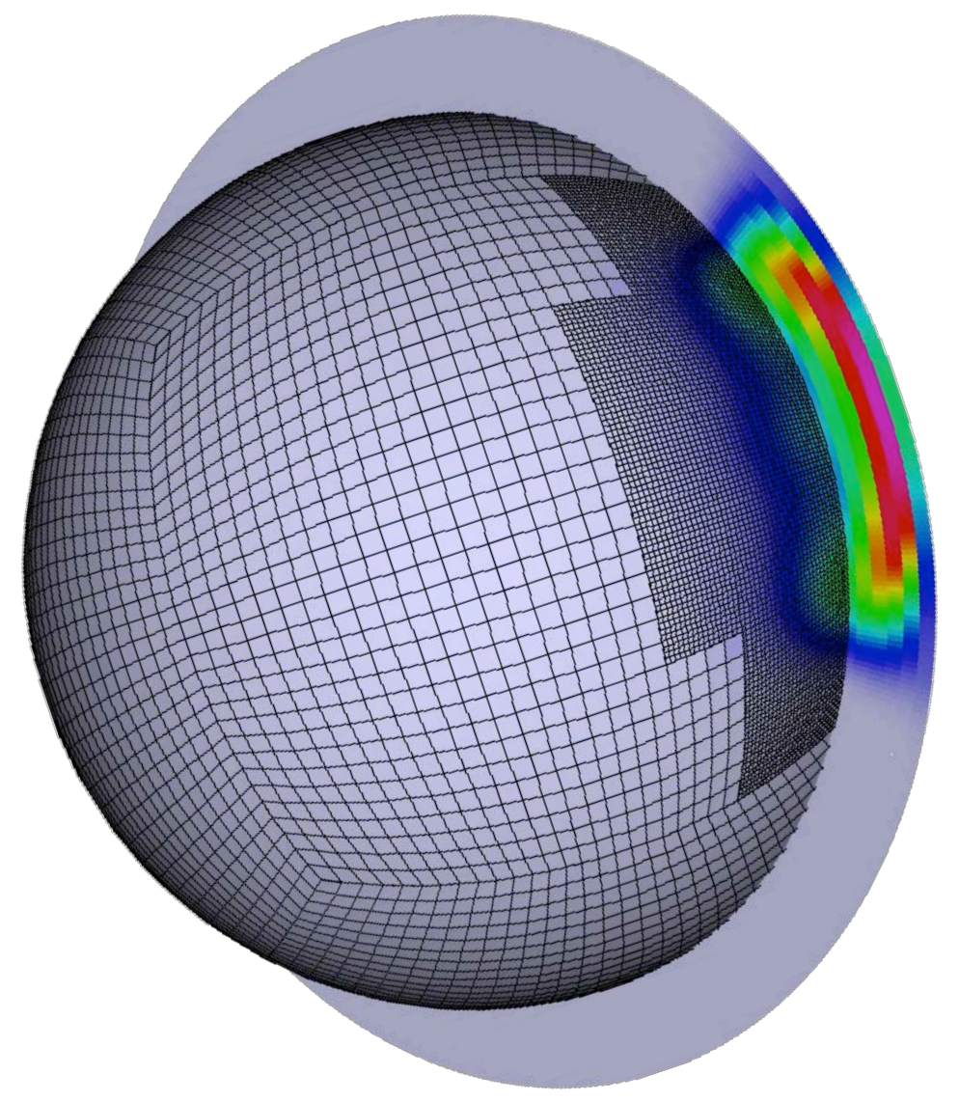

Fig 12: Hadley cell advecting tracer to upper atmosphere, with horizontal refinement.

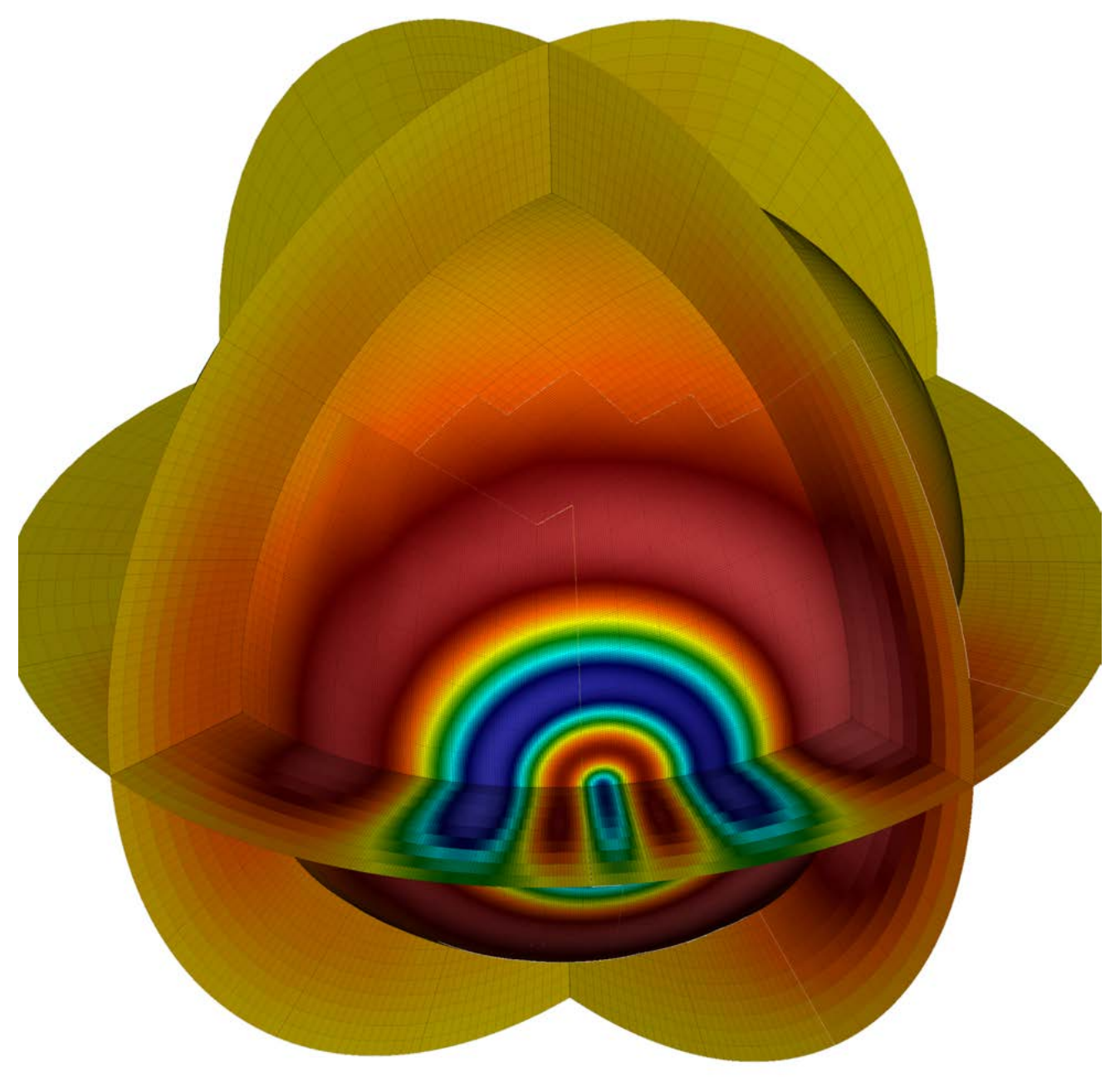

Fig 13: A dynamic gravity wave experiment using adaptive mesh refinement to track the disturbance. Cells are tagged for refinement in this case based on the magnitude of the potential temperature perturbation.

Refinement based on tracking of active features is under development, for use in understanding tropical cyclones, atmospheric rivers are associated features with strong resolution dependence. New physical parameterizations are also being developed with behavior that smoothly transitions across refinement boundaries.

Future Work

The techniques used to construct the AMR dycore will benefit the climate modeling community for years to come. Parameterization of certain physical processes continues to be unavoidable. Even as model resolutions become finer and computational resources more powerful, multiscale grids will continue to act as an efficient intermediate step between feasible globally uniform grid resolutions and those just beyond our capabilities.

Coming soon:

- Integration of Chombo into the Community Earth System Model (CESM) framework.
- Integration of System for Atmospheric Modeling (SAM) physics for integration at the cloud-resolving scale.
- High-order treatment of orography, including new techniques for avoiding pressure gradient errors.

References

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