Introduction / Motivation

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

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 dynamical features (e.g. clouds, atmospheric rivers)
- Regional weather phenomena (e.g. tropical cyclones, coastal climate)
- Grid refinement studies for new physics (cloud parameterizations)
- Evaluation of time discretization errors from 10 operator splitting ("volume physics")

Non-Hydrostatic Equations and Grids

We follow the approach in [UO2012], which discretizes spherical shells (atmospheric levels) using:

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

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

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

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

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 shown to exhibit 4th-order scalability [NKJ2014].

Non-Hydrostatic Flow on the Sphere

Testing is ongoing on the development of AMR for 3D non-hydrostatic dynamics. Different grids can be used for different tracer species, and for dynamical features such as orography. A number of outstanding problems are underlying 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.

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.

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 [UO2014]. This framework uses a spectral element discretization in the horizontal direction and finite element vertical discretization for solving the non-hydrostatic equations of motion.

Future Work

The techniques used to construct the AMR dynco 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, multivariate 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