Variable resolution experiments using CAM-SE

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Motivation

- 2015 Goal: High-resolution version of the Community Atmosphere Model (CAM) with improved representation of the hydrologic cycle and running efficiently (5 SYPD) on both DOE LCFs.
- Target resolution: 1/8 degree (13.5km)
- Variable resolution used as a test-bed to develop, tune and evaluate parameterizations at 1/8 degree resolution
- The test-bed concept is a simple application of multi-resolution that can be used today - does not require scale-aware parameterizations
Outline

- Overview of CAM-SE
- Global 1/8 degree (13.5km) and variable resolution (1 degree to 1/8 degree) AMIP simulations
- Tensor hyperviscosity formulation for unstructured conforming non-orthogonal grids
- Evaluation of the impact of localized mesh refinement on global error in shallow water tests.
CAM-SE Dynamical Core

- **Hydrostatic equations in hybrid sigma/pressure terrain following “eta” coordinate**
- **Dynamics: modeled after CAM-EUL**
  - SE used for horizontal discretization
  - S&B MWR 1981 vertical discretization
  - KE dissipation: hyperviscosity
  - RK2 m-stage time-stepping
- **Tracer Transport: modeled after CAM-FV**
  - SE used for horizontal discretization (with quasi-monotone bounds-preserving limiter)
  - Vertically Lagrangian (S.J. Lin 2004) with monotone remap (Zerroukat et. al, QJRMS 2005.)
  - RK2-SSP 3 stage time-stepping exactly preserves all monotonicity properties of spatial discretization.
Spectral Element Method

- CG finite element method with quadrature-based inner-product (diagonal mass matrix)
- Simple $Q^3$-$Q^3$ element (velocity and pressure are both in $Q^3$), stabilized with hyper-viscosity
- Mimetic discretization (Taylor & Fournier JCP 2010):
  - Discretization preserves adjoint properties of DIV, GRAD and CURL operators:
    - Local conservation of quantities in conservation form (mass, tracer mass)
    - Semi-discrete conservation of energy
  - $\text{CURL GRAD} = 0$
    - Local conservation of 2D PV
    - Stationary geostrophic modes (f-plane)
CAM5-SE at 1/8°

Global 1/8°
CAM5-SE has a very efficient, scalable and expensive global 1/8° configuration.

- 6M core hours per year (ANL Intrepid)
- Yellowstone: 1-2M core hours?
- 3.1M physics columns, 26 tracers
- dtime=600, dt=37.5s

SGP 8x Regionally Refined
1° global resolution, refined to 1/8° continental sized region centered over SGP ARM site.

- 0.12 M core hours per year (Sandia Linux cluster).
- 67K columns, 26 tracers
- dtime=600, dt=31.6
CAM5 Regionally Refined
1° global resolution, refined to 1/8°
Precipitable water (gray), precip rate (color), sea level pressure (contours)

Global 1/8° Simulation
Snapshots show propagating convective system not seen at lower resolutions. Detailed frontal structure and tapping of moisture

Regionally Refined Simulation
Similar convective systems form in the 1/8° region, strongly dissipated as it propagates into the 1° region
Precipitable water (gray), precip rate (color), sea level pressure (contours)
Variable Resolution
AMIP and APE climate results

- Latest results presented in the Newton Institute’s first workshop
  - http://www.newton.ac.uk/programmes/AMM/ammw01.html
- Compare climate in the high-resolution region from a variable resolution simulation with the climate from global high-resolution
- Detailed results for Aqua planet, preliminary results for diurnal cycle of U.S. midwest precipitation.
Variable resolution & dissipation

- Initial runs showed ugly precipitation artifacts in grid transition region
- Tried various grid-smoothing techniques which had little effect
- Best results obtained with careful resolution scaling of hyperviscosity coefficient
  - In high-res region, match coefficient used in global high-res
  - In low-res region, match coefficient used by global low-res
  - Smooth variation in mesh transition region
Tensor hyperviscosity for non-orthogonal quadrilateral grids

- Our best results obtained with tensor HV coefficient
- Main advantage: allows coefficient to scale independently for both length scales of the quadrilateral
- Length scales $dx$ and $dy$ are given by the eigenvalues of the symmetric 2x2 matrix $D'D$, where $D$ is the derivative of the map to the reference element
- Tensor coefficients are smoother in the transition region than when using a constant coefficient based on a single length scale
Results consistent with Ullrich & Jablonowski JCP 2011

- Spurious waves at abrupt (2:1) mesh transitions:
  - C-grid: spurious reflected waves can be large scale, difficult to damp so they must be minimized by using smooth transitions
  - A-grid: spurious reflected waves are at the grid scale
    - Can handle abrupt transitions with effective control of grid scale waves
    - A-grid methods already require stabilization mechanisms for 2dx-4dx waves
    - We’ve seen a variety of collocated methods using 2:1 refinement (DG codes and MCORE/Chombo FV)
    - CAM-SE: use conforming mesh refinement in order to preserve mimetic properties of the method
Shallow water tests

- Evaluate tensor-HV with shallow water test cases
  - Ensure mesh refinement does no harm (St-Cyr MWR 2008, Weller et al., MWR 2009, Ringler et al., MWR 2011)
  - Measure convergence rates with highly unstructured meshes
  - Follow Ringler2011 and look at convergence as a function of the low-resolution grid spacing, for 4 suites of grids: uniform, x2, x4 and x8

330km (3 degree) x8 grid
Quasi-uniform 330km grid, with 8x refinement (41km) over test case 5 mountain
SW Test 2, geostrophic balance

- Normalized $l_2$ error at day 12 (not day 5, per Ringler et al. 2011)
- With no stabilization: $l_2$ error convergence rate: 4.0
- TensorHV, $\nu \sim dx^4$: $l_2$ error convergence rate: 3.5
- TensorHV, $\nu \sim dx^{3.2}$: $l_2$ error convergence rate: 2.8
- With TensorHV, introduction of refinement does not change error
SW Test 5, flow past a mountain

- Normalized $l_2$ error at day 15.
- Refinement over mountain always (slightly) reduces global error
- Within the $x2,x4,x8$ suite of grids, additional refinement does not change errors
- Uniform grid: $l_2$ error rate starts out at 5, dropping to 1.8 as we approach reference solution uncertainty
Summary

- CAM-SE variable meshes are working as hoped:
  - High-res features captures in high-res region of variable-resolution grids
  - Tensor-HV stabilization: effective stabilization for conforming unstructured quad grids
  - SE mesh refinement does no harm: preserves order of accuracy of the method even with highly unstructured grids

- Future work: better stabilization with VMS?
  - Flow dependent (not grid resolution dependent)
  - Marras et al., JCP 2011
  - M. Moragues et al., PDEs on the sphere 2012
Backup Slides
Initial simulation with stationary artifacts in grid transition region

Artifacts eliminated with improved variable-coefficient hyperviscosity operator.

Precipitable Water (kg/m^2)
Initial results showed ugly stationary grid artifacts at transition boundaries.

CAM5 AMIP on SGP 8x grid

Precipitable Water (kg/m^2)
“SGP 8x” Variable Resolution Grid
1° global -> 1/8° regional

Unsmoothed
Grid generated with CUBIT GUI-based meshing tool. Starting with global grid, apply refinement in selected regions.

Smoothed
CUBIT’s Winslow smoothing option uses metric appropriate for spectral elements. But also smooths the cube corners – Need option to apply smoothing in limited region.
Tensor Hyperviscosity for non-orthogonal grids

\[ \frac{\partial u}{\partial t} = \nu \nabla \cdot \nabla u \]

\[ \int \phi \frac{\partial u}{\partial t} = -\nu \int \nabla \phi \cdot \nabla u \]
Tensor Hyperviscosity for non-orthogonal grids

\[ \nu \nabla \phi \cdot \nabla u \simeq \nu \begin{pmatrix} \phi_x \\ \phi_y \end{pmatrix}^t D^t D \begin{pmatrix} u_x \\ u_y \end{pmatrix} \]

\[ = \nu \begin{pmatrix} \phi_x \\ \phi_y \end{pmatrix}^t U^t \begin{pmatrix} \Delta x & 0 \\ 0 & \Delta y \end{pmatrix}^{-2} U \begin{pmatrix} u_x \\ u_y \end{pmatrix} \]

\[ \left( \begin{pmatrix} \phi_x \\ \phi_y \end{pmatrix}^t U^t \begin{pmatrix} \nu_1 \Delta x & 0 \\ 0 & \nu_2 \Delta y \end{pmatrix}^{-2} U \begin{pmatrix} u_x \\ u_y \end{pmatrix} \right) \]
The Community Earth System Model (CESM)

- IPCC-class model developed by NCAR, National Labs and Universities
- Atmosphere, Land, Ocean and Sea ice component models
- CAM is the atmosphere component model
- Science & policy applications:
  - Seasonal and interannual variability in the climate
  - Explore the history of Earth's climate
  - Estimate future of environment for policy formulation
  - Contribute to assessments
Spectral Element Method

- Spectral Elements: A Continuous Galerkin Finite Element Method
  - Galerkin formulation, with basis/test functions: degree $p$ polynomials within each element, continuous across elements ($Q^p$-$Q^p$ element, with $p=3$ typical)
  - Gauss-Lobatto-Legendre quadrature based inner-product (requires quadrilateral elements)
  - GLL inner product + nodal basis gives a diagonal mass matrix. (Maday & Patera 1987)
Galerkin formulation of the equations leads to a 2 step solution procedure:

- **Step 1:** All computations local to each element and on a tensor-product grid. Structured data with simple access patterns and arithmetically intensive operations: Extremely efficient on modern CPUs or GPUs.
- **Step 2:** Apply inverse mass matrix (projection operator).
Galerkin FE Approach Ideal for Modern Architectures

- All inter-element communication is embedded in Step 2, providing a clean decoupling of computation & communication.
  - Only a single routine has to be optimized for parallel computation.
Aqua Planet Experiments

How well does the climate in high-resolution region of a variable resolution simulation match climate of a global high-resolution simulation?
Aqua Planet

- Full Atmospheric physics and dynamics, on a planet with no land and a fixed sea surface temperature (Neale & Hoskins, 2000a: *A standard test for AGCMs including their physical parameterizations*, Atmos. Sci. Lett.)

- No convergence under mesh refinement, as expected due to the nature of many of the subgrid physics parametrizations

- Strong signal with resolution (CAM4)

- Resolution signal is consistent across dycores allowing one to establish equivalent resolutions (Williamson, Tellus 2007)
- CAM4 APE shows strong signal under mesh refinement, similar to that seen in CAM3.1 APE (Williamson, Tellus 2007)
- Focus on two quantities examined in Williamson 2007 with some of the largest resolution sensitivity: cloud fraction and large scale precipitation.
Cloud Fraction

2° Global

APE 8x grid

1/4° Global

APE 8x - 1/4° Global
APE Variable Resolution

- Compare $\frac{1}{4}^\circ$ global uniform resolution climate with the climate in the $\frac{1}{4}^\circ$ region from a variable resolution simulation
- APE 8x grid: $2^\circ$ transitioning to $\frac{1}{4}^\circ$ in large equatorial region
- Following DOE Robust Regional Modeling Project evaluation strategy: Rauscher et al., under review, *Exploring a Global Multi-Resolution Modeling Approach Using Aquaplanet Simulations*
- Levy et al., under review, *A variable resolution spectral element dynamical core in the Community Atmosphere Model*
Cloud Fraction

2° Global

1/4° Global
Large scale precip

2° Global

1/4° Global

APE 8x grid

APE 8x - 1/4° Global
AMIP Simulations: Mid-west propagating systems
US mid-west diurnal propagating systems

June-July

UT [hr]

Diurnal Rainfall Rate [mm/hr]

LST [hr]

Tropical Rainfall Measuring Mission (TRMM) (35-45N, mm/day)
Midwest propagating systems

- Some improvements going from 1° to 1/8°, captured in both global high-res and variable resolution simulations
  - Diurnal cycle improved (weak 12h mode becomes strong 24h mode), with some eastward propagation
  - Precip max improved, but occurs too early and does not propagate
- Variable resolution simulation
  - In 1/8° region: reasonable agreement with global high-res simulation
  - Also remarkable agreement at 80W (in 1° region) downstream from 1/8° region
Precip Hovmoller Diagrams
June-July 1° Resolution

TRMM

Composite TRMM June and July Precipitation (N. America)

Global 1°

CAM5 1° June and July Precipitation (N. America)
June-July 1/8°

**TRMM**

2000-2004

**Global 1/8°**

2005-2006

**Variable Resolution**

2000 cyclic YEAR 1-4