CAM/HOMME: Parallel Scalability and Aqua Planet Results for CAM on the cubed-sphere grid

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CCSM Workshop SEWG session, Breckenridge, June 2008

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The Dynamical Core Experiment: An Overview of the 2008 NCAR ASP Colloquium

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Overview

The poster gives an overview of the 2008 NCAR ASP summer colloquium that took place in Boulder, CO, from June 2-13/2008. The colloquium titled "Numerical Techniques for Global Atmospheric Models" surveyed the latest developments in numerical methods for the dynamical cores of Atmospheric General Circulation Models. The primary sponsors were the NCAR Advanced Study Program (ASP) and NASA. The objectives of the colloquium were (1) to teach a large group of graduate students in atmospheric science and mathematics how today's and future dynamical cores are or need to be built, (2) to invite almost 10 dynamical core modeling groups to NCAR for an unprecedented student-run dynamical core intercomparison project, (3) to establish new dynamical core test cases in the community and (4) to invite keynote speakers to NCAR that give lectures on modern numerical techniques and innovative computational meshes.

The poster surveys the achievements of this 'Dynamical Core Experiment' that will now serve as a launch pad for an even broader community-driven dynamical core intercomparison project.

Brief description of the dynamical cores

Nine dynamical core modeling groups participated in the colloquium:

1) GISS-EQ (NASA Goddard Institute for Space Studies, New York, NY): 2nd order centered differences plus quadratic upstream FV, latitude-longitude grid, B-grid staggering, hybrid (η) vertical coordinate
2) CAM Eulerian (NCAR, Boulder, CO): spectral transform method with triangular truncation, Gaussian grid, hybrid (η) vertical coordinate
3) CAM FV with isentropic vertical coordinate (NCAR, Boulder, CO): finite-volume (FV) approach with monotonicity constraints (PPM), latitude-longitude grid, D/C-grid staggering, floating Lagrangian vertical coordinate with hybrid isentropic coordinate as reference grid
4) GEOS FV (NASA Goddard Space Flight Center, Greenbelt, Maryland): same as 3) but with pressure-based hybrid (η) vertical coordinate as reference grid
5) GEOS FV on a cubed sphere grid (NASA Goddard Space Flight Center, Greenbelt, Maryland): same as 4) but with a cubed-sphere computational grid, less implicit diffusion due to high-order interpolations
6) GME (German Weather Service DWD, Offenbach, Germany): 2nd order finite differences, icosahedral grid, A-grid staggering, hybrid (η) vertical coordinate
7) HOMME (NCAR, Boulder, CO): spectral element method, cubed-sphere grid with gnomonic projection, Gauss-Lobatto quadrature points within each spectral element, hybrid (η) vertical coordinate
8) ICON (Max-Planck Institute for Meteorology, Hamburg, Germany and DWD): finite difference method, icosahedral grid, C-grid staggering, hybrid (η) vertical coordinate
9) OLAM (Duke University, NC): nonhydrostatic, finite volume method, C-grid staggering, height coordinate with shaved grid cells

Models (1)-(8) are hydrostatic and based on the Primitive Equations set. All models were run in their operational configurations which included their typical diffusion mechanisms such as horizontal divergence damping, horizontal 2nd order diffusion and 4th order hyperdiffusion, 3-point digital filters, Shapiro filters, monotonicity or flux limiting constraints in Finite Volume algorithms and Asselin time filtering for 3-time-level schemes (EQ, EUL, GME). See also: Earth System Grid http://dycore.ucar.edu/

Idealized test cases for dynamical cores: The dynamical core intercomparison

The test suite consists of 6 dynamical core test cases with multiple variants. The test case families are:

- Steady-state initial conditions (not shown here)
- Evolution of a baroclinic wave with additional tracer advection
- Pure 3D advection test with prescribed wind speeds
- Rossby-Haurwitz wave with wave number 4 pattern
- Mountain-induced Rossby waves triggered by idealized orography
- Gravity wave tests with and without the Earth's rotation

All models were tested with identical initial conditions. The results shown here were run at a medium high horizontal resolution which corresponds to approximately 1°x1°. The number of vertical levels was 26 (test 2, 4, 5), 60 (test 3) and 20 in test 6. The complete description of the test cases can be found on the Wiki web page "https://wiki.ucar.edu/display/dycores/Test+cases" and in the attached document below.

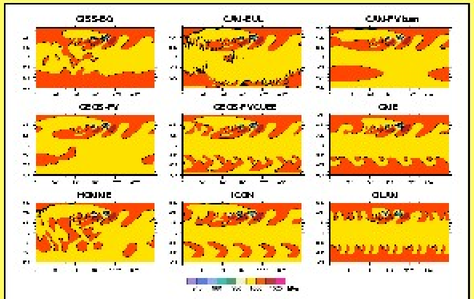


Fig. 1: Test case 2-0-0 (Baroclinic wave test): Surface pressure at day 9. The test starts with balanced initial conditions that are overlaid by a Gaussian hill perturbation. The perturbation grows into a baroclinic wave. The grid imprint of the cubed-sphere and icosahedral grids can be seen in the Southern Hemisphere (GEOS-FVCUBE, GME, ICON, OLAM). Spectral ringing appears in CAM-EUL and HOMME. The baroclinic wave test is documented in Jablonowski and Williamson, QJ (2006) and in the Jablonowski and Williamson NCAR Technical Report TN-469+STR (2006).

Fig 2: Group photo of the participants of the NCAR ASP 2008 summer colloquium taken on 6/11/2008 behind NCAR's Mesa Lab. 9 dynamical core modeling groups and mentors, 36 graduate students from U.S. and international universities and 17 lecturers participated in the 2-week summer school.

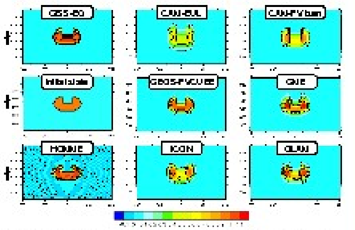
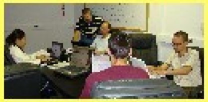


Fig. 3: Test case 3-0-0 (3D Advection Test): Latitude-height cross section of a 3D slotted ellipse tracer distribution after one revolution around the sphere (day 12). The 3D wind speeds are prescribed. The slotted ellipse has followed a trajectory path with three wave cycles in the vertical direction. The test evaluates the diffusion characteristics of the advection algorithm.



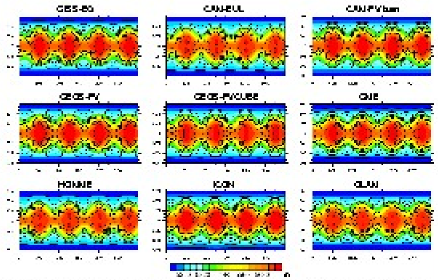


Fig. 4: Test case 4-0-0 (Rossby-Haurwitz wave): 500 hPa geopotential height at day 15. The wave number 4 pattern is expected to move westward without change of shape. At day 15 some variations of the shape are apparent that are caused by the characteristics of the numerical schemes.

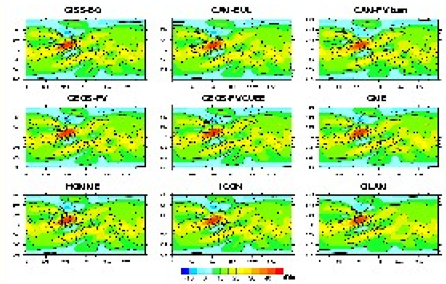


Fig. 5: Test case 5-0-0 (Mountain induced Rossby waves): 700 hPa zonal wind at day 15. The test starts with balanced and isothermal initial conditions. A 2-km high Gaussian-hill shaped mountain with half-width 1.5 km is placed at (90°E, 30°N) (not shown). The mountain triggers Rossby waves. The test evaluates the treatment of the orography and reveals numerical noise (especially at later days).

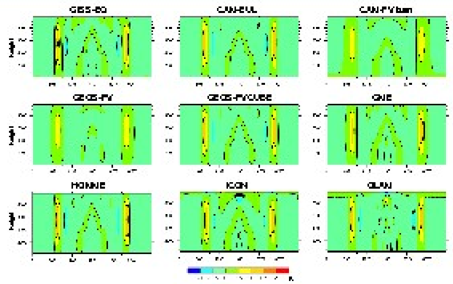
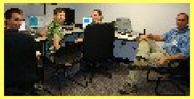
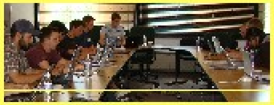


Fig. 6: Test case 6-0-0 (Pure Gravity Wave Test): Longitude-height cross section along the equator of the potential temperature perturbation at day 4. The Coriolis parameter is set to zero. The test reveals the influence of the diffusion and damping mechanisms in the dynamical cores. In particular, the divergence damping leads to a significant decrease in the gravity wave amplitude in FV (CAM & GEOS). Diffusion also influences the sharpness of the gradient. Reflections at the top appear in ICON and OLAM.





We thank our sponsors, modeling mentors and students for their support and dedicated work:
Sponsors:
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Student Participants:
[illegible]

Figures were plotted by [illegible] (University of Michigan)

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CAM/HOMME: Parallel Scalability and Aqua Planet Results for CAM on the cubed-sphere grid

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Outline

- **Integration of NCAR's HOMME into CAM**
  - Process-split physics/dynamics interface (Williamson MWR 2002)
  - Physics/dynamics splitting infrastructure (Worley & Drake, IJHPCA 2005)
- **Motivation: Petascale-ready version of CAM**
  - BG/L and BG/P benchmark results on up to 86,200 processors
- **Evaluation using Aqua Planet Experiments**
  - Neale & Hoskins, Atmos. Sci. Lett. 2000
  - Williamson, *Convergence of aqua planet simulations with increasing resolution in the Community Atmospheric Model*, *Version 3*, Tellus, to appear
  - Williamson, *Equivalent Finite Volume and Spectral Transform Horizontal Resolutions Established for Aqua-planet Simulations,* Tellus, to appear

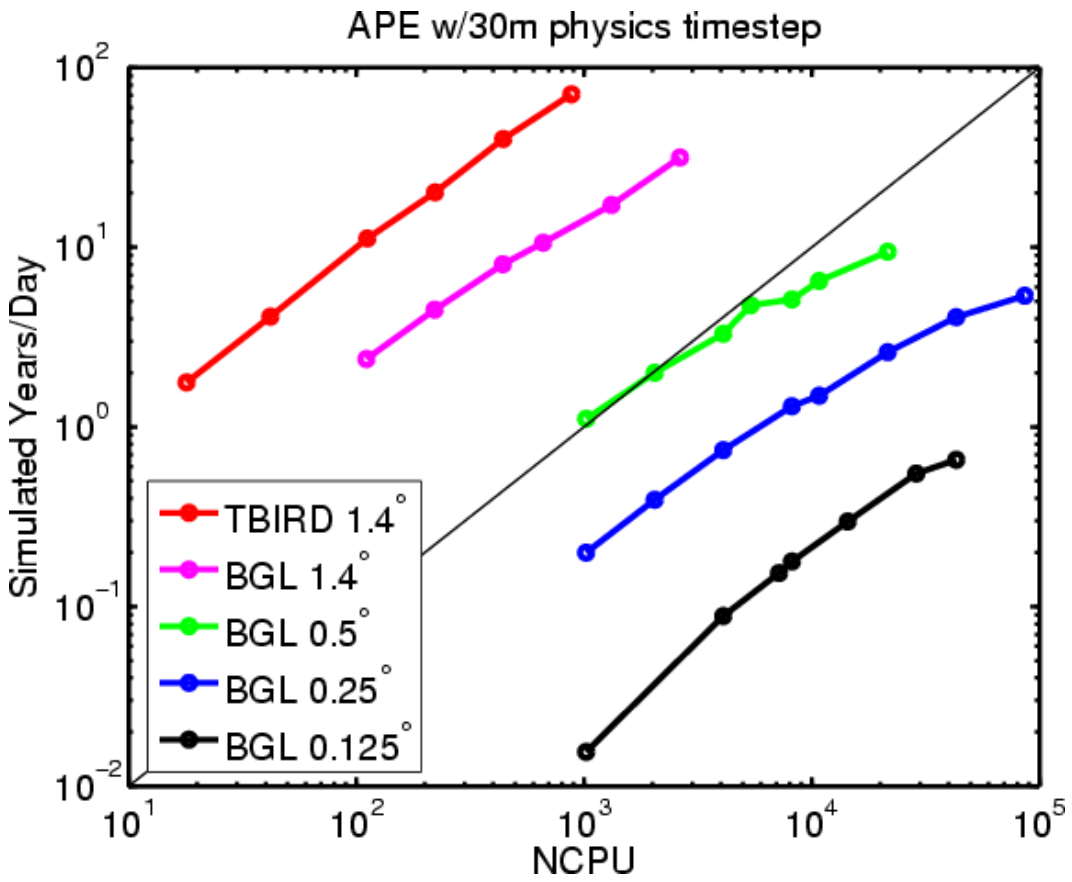
CAM/HOMME
Spectral Element Dynamical Core

- *h-p* Finite element method on a cubed-sphere grid
- Exactly conserves dry mass
- Energy conservation is semi-discrete: (exact with exact timestepping)
- KE dissipation added via hyper-viscosity
- Tracer advection: consistent with mass equation, positive preserving, but not monotone
- No pole problem allows for full 2D domain decomposition

Aqua Planet Experiments

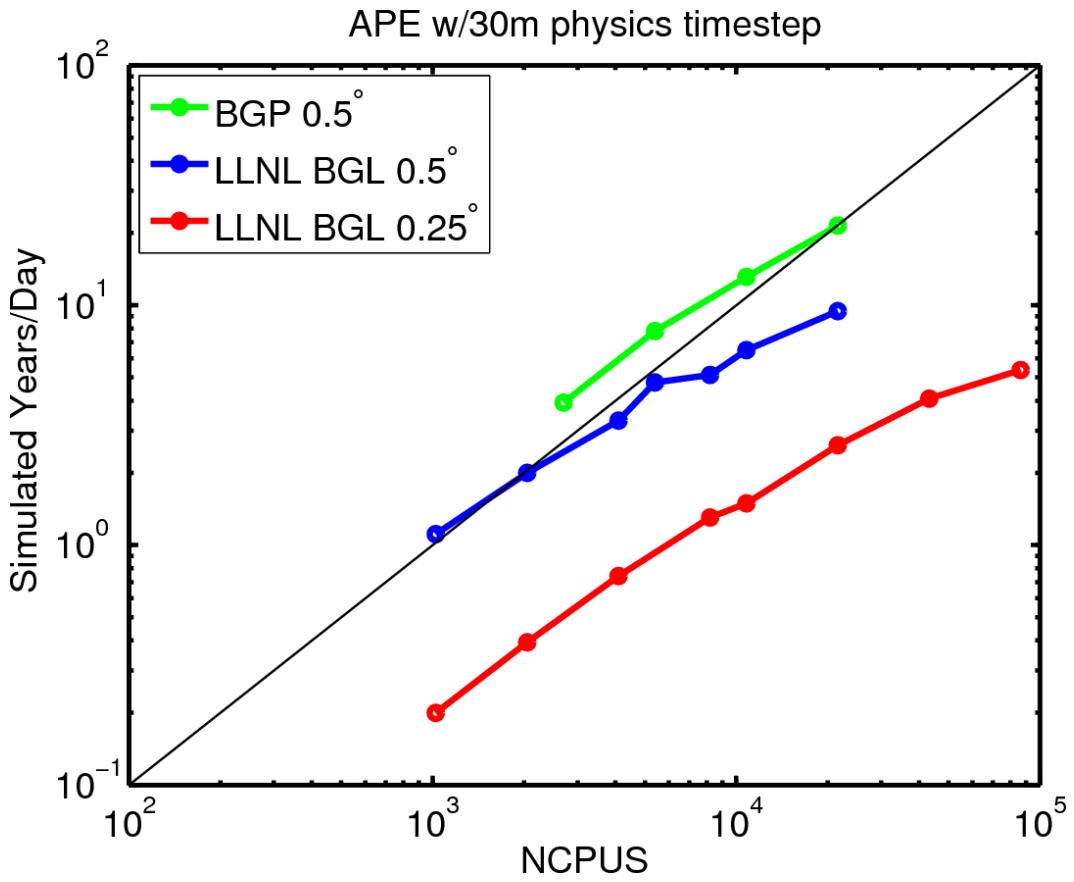
- Follow Williamson equivalent resolution methodology
- CAM 3.1 Physics
- 14 month simulations
- 5min physics timestep used for model comparisons
- 30min physics timestep used for benchmarks
- Eulerian T85 physics tuning (all models)
- Eulerian and FV results taken from Williamson, Tellus 2008a, 2008b
- Additional results: http://swiki.ucar.edu/ccsm/86

Fixed Mesh Scalability on LLNL BG/L



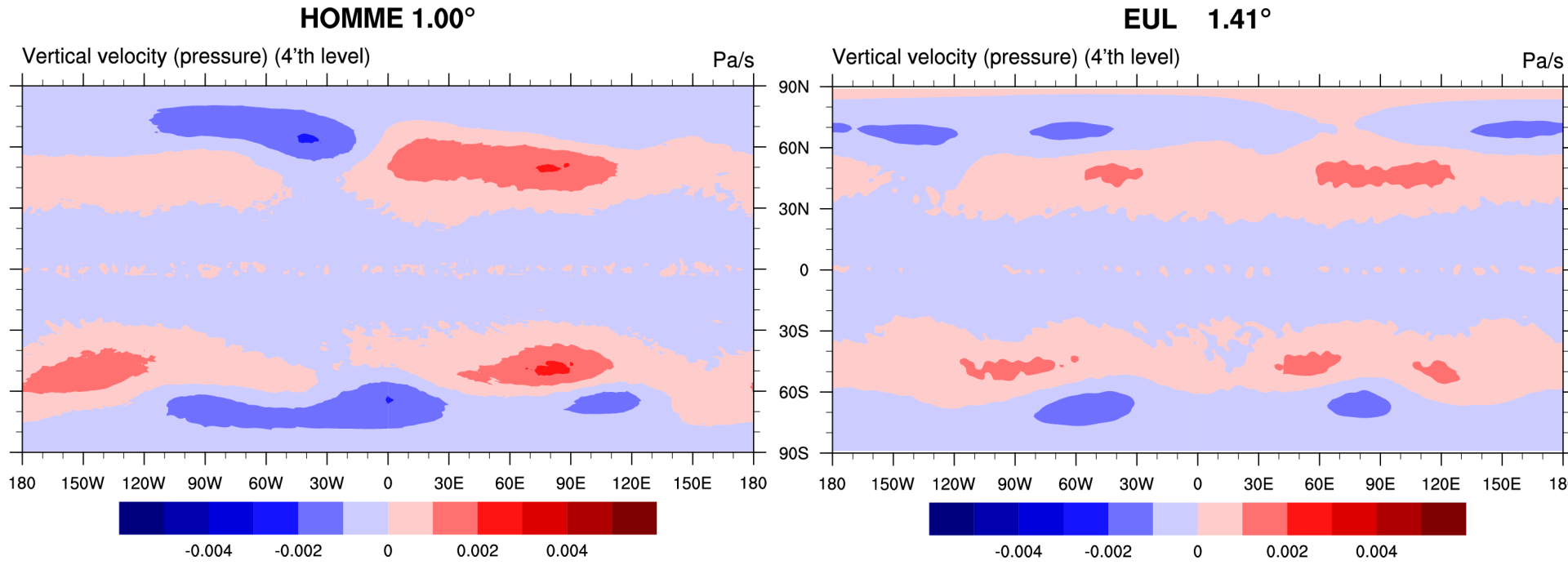
- Good scalability down to 1 element per processor (86,200 processors at 0.25 degree resolution). Higher resolutions will easily scale to even more processors
- BG/L achieves integration rates better than 5 simulated years/day at resolutions down to 0.25 degree

Fixed Mesh Scalability on ANL BG/P



- Each core is about 2x faster
- BG/P results use 4 processor cores per node. BG/L used 1 processor per node due to memory constraints.
- Thus each BG/P node is effectively 8x faster than a BG/L node.

Minimal cubed-sphere grid imprinting



Pressure vertical velocity contoured on the 4'th eta-level. Noise characteristics quite similar to the near perfectly isotropic Eulerian model.

This field is one of the most sensitive to grid imprinting. See for example Wyman et al. (SEWG 2007 presentation) from GFDL FV cubed-sphere aqua planet simulations.

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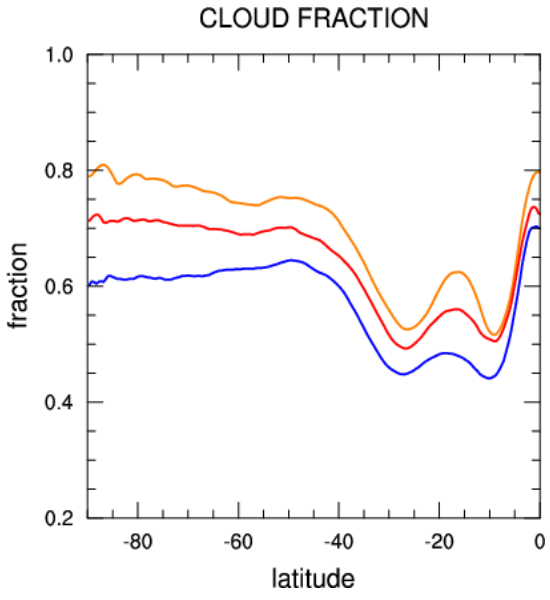
Aqua Planet Global Mean Quantities

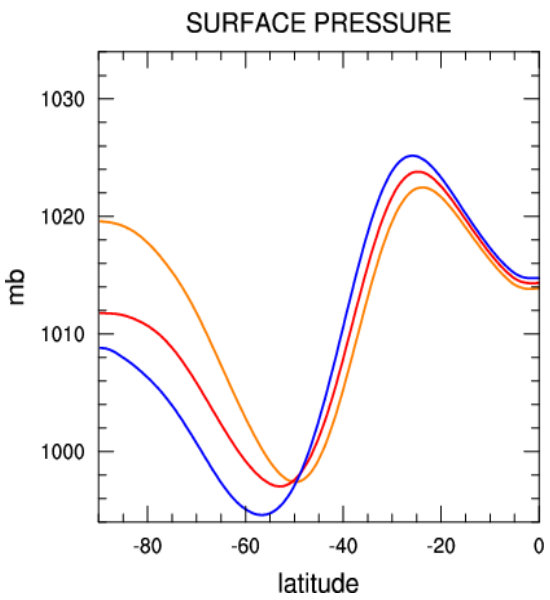
Resolution	Physics dt	Viscosity	PRECC	PRECL	CLDTOT	TMQ
EUL T42	5m	1.0E+16	1.71	1.11	0.64	20.21
HOMME 1.9	5m	1.0E+16	1.76	1.14	0.66	20.09
EUL T85	5m	1.0E+15	1.59	1.38	0.60	19.63
HOMME 1.0	5.5m	1.0E+15	1.59	1.43	0.61	19.67
HOMME 1.0	5.5m	3.0E+14	1.45	1.58	0.59	19.71
EUL T170	5m	1.5E+14	1.44	1.62	0.55	19.13
HOMME 0.5	5m	1.5E+14	1.48	1.62	0.55	19.36
HOMME 0.5	5m	5.0E+13	1.39	1.70	0.53	19.18
T340	5m	1.5E+13	1.36	1.75	0.50	18.75

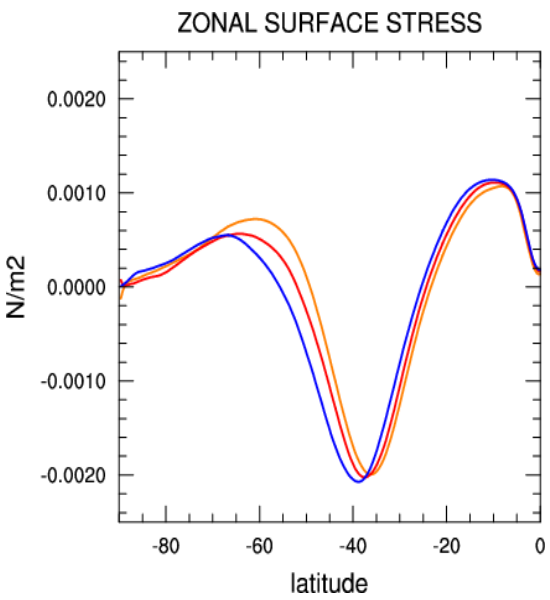
Compared to the size of the resolution signal, there is a remarkable agreement between CAM/HOMME and CAM/Eulerian

Aqua Planet Experiment: Zonal Data Comparison with FV & Eulerian Dycore

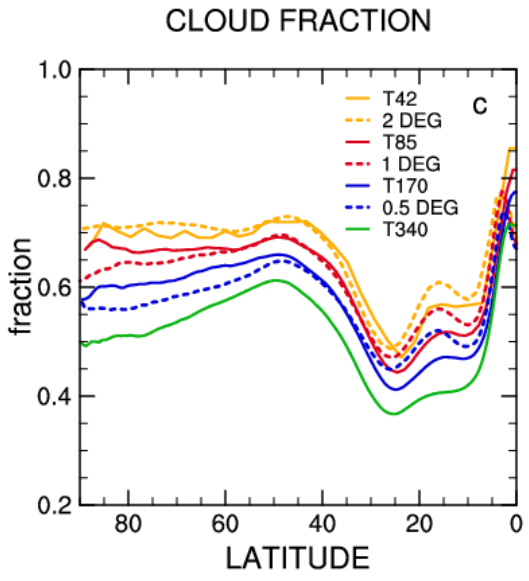
HOMME

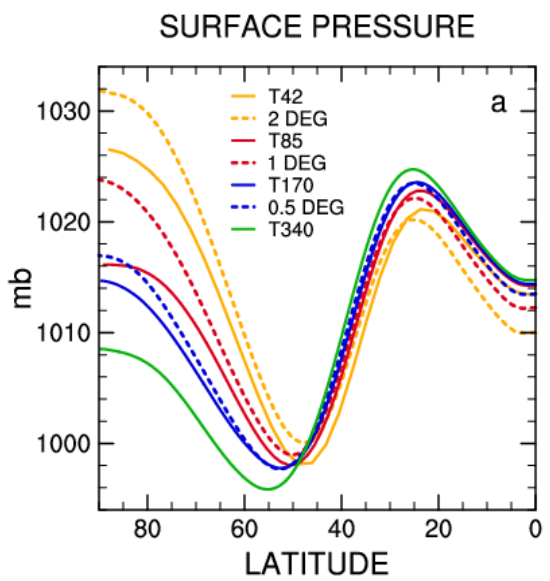


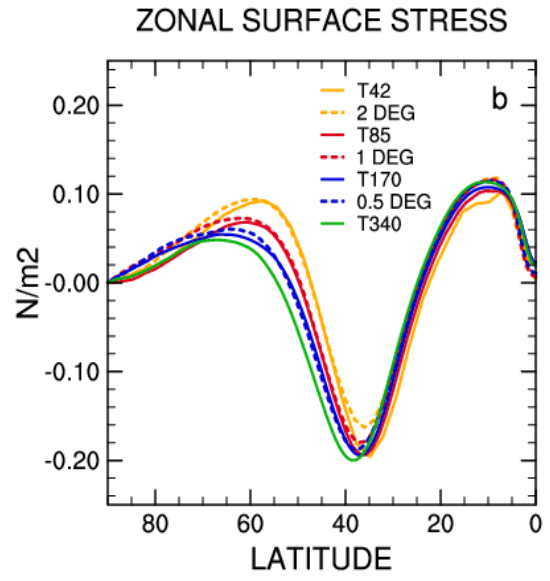




FV & Eulerian





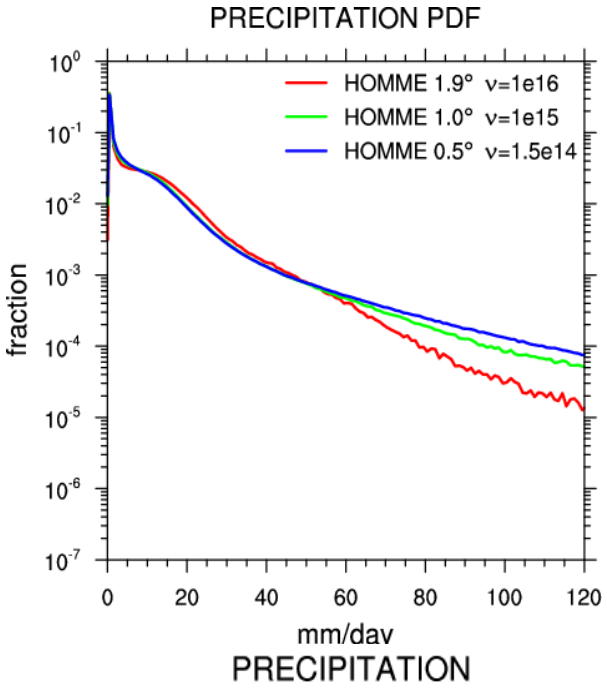


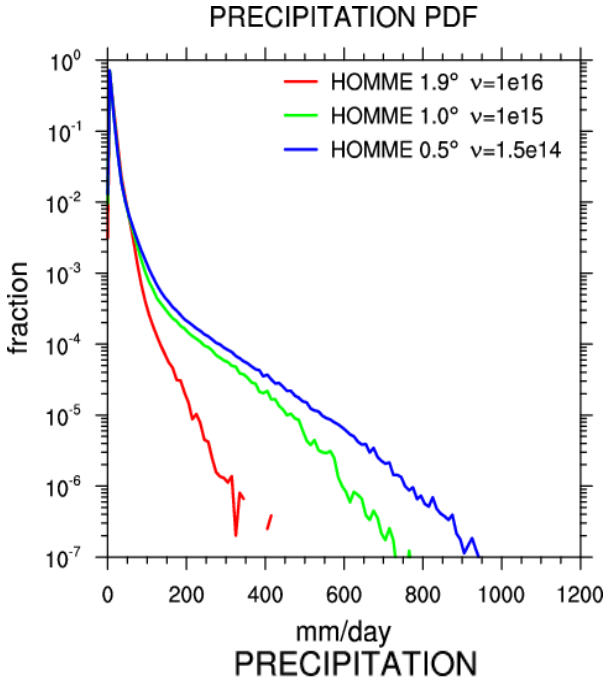
Precipitation PDFs

1mm bin-size

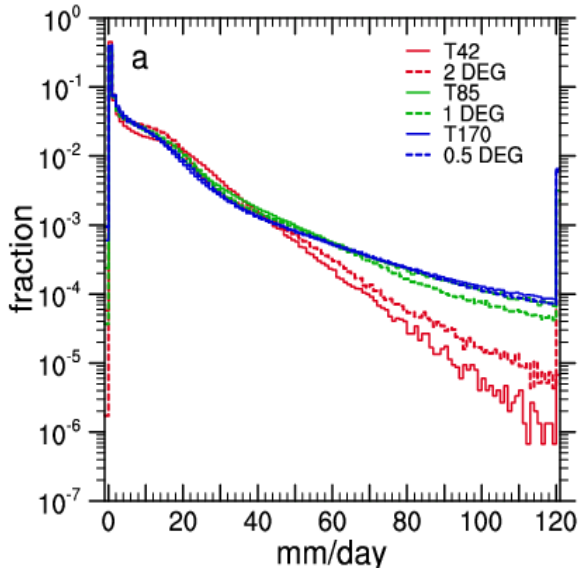
10mm bin-size

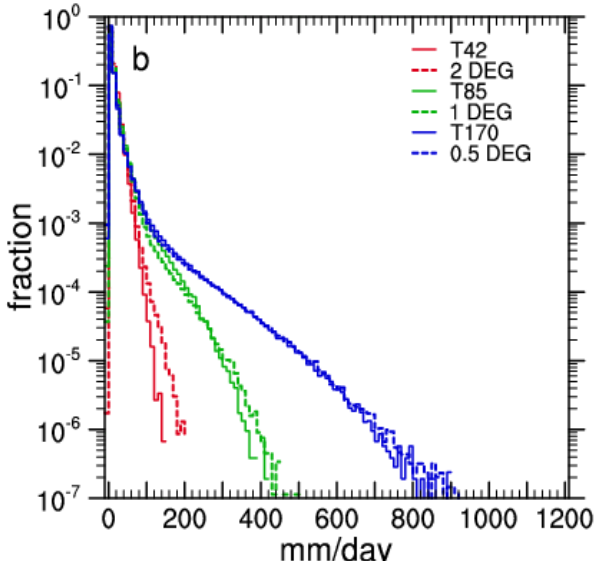
HOMME





FV & Eulerian

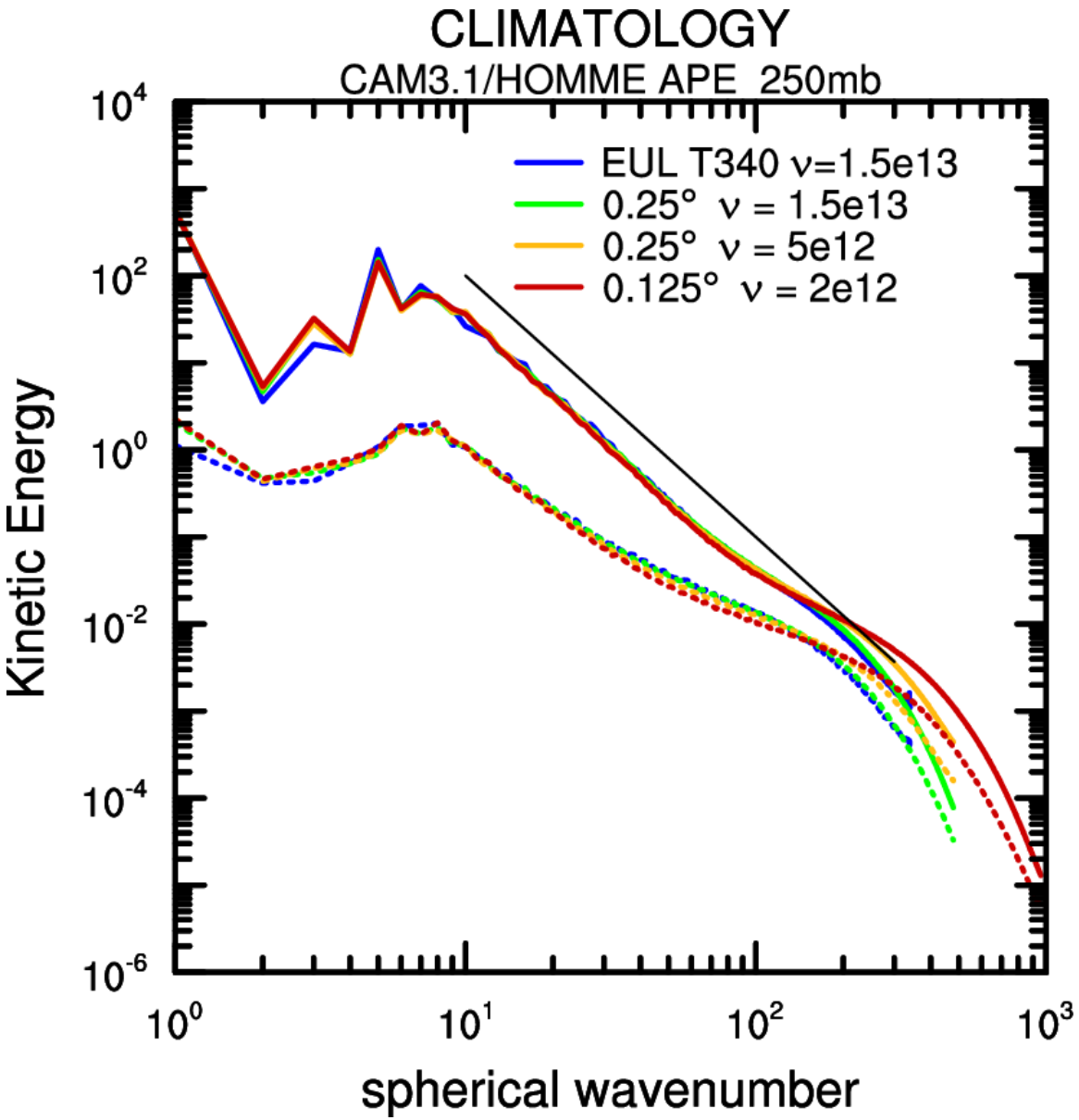




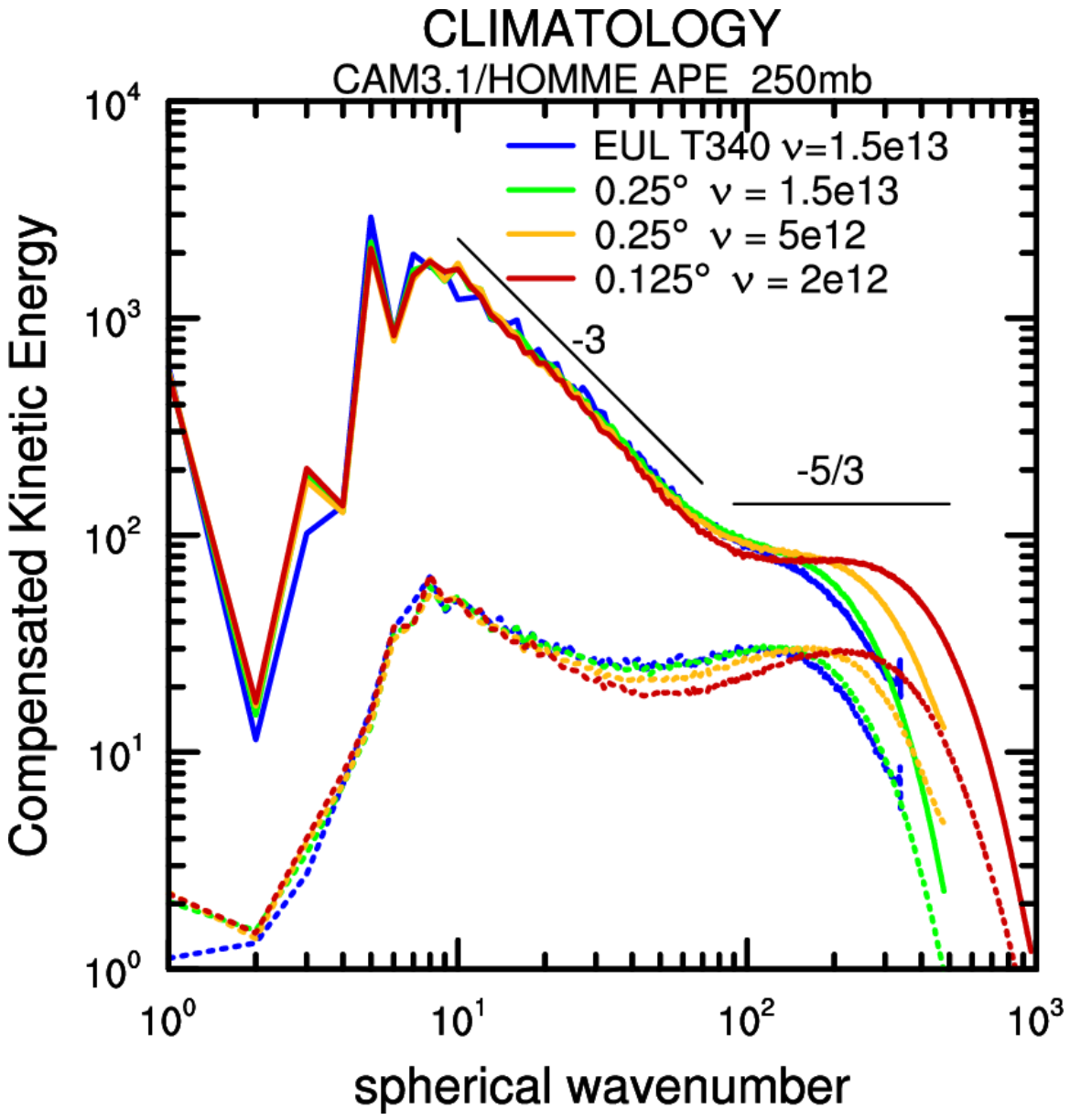
High Resolution Aqua Planet Experiments

- CAM 3.5 Physics
- 14 month simulations
- 5min physics timestep
- Eulerian T85 physics tunings
- Simulations on LLNL BG/L system
  - 0.250 degree: 43200 processors ~1 day per simulation
  - 0.125 degree: 57600 processors ~3 days per simulation (done with no restart!)

High Resolution Results - CAM 3.4 Physics



High Resolution Results - CAM 3.4 Physics

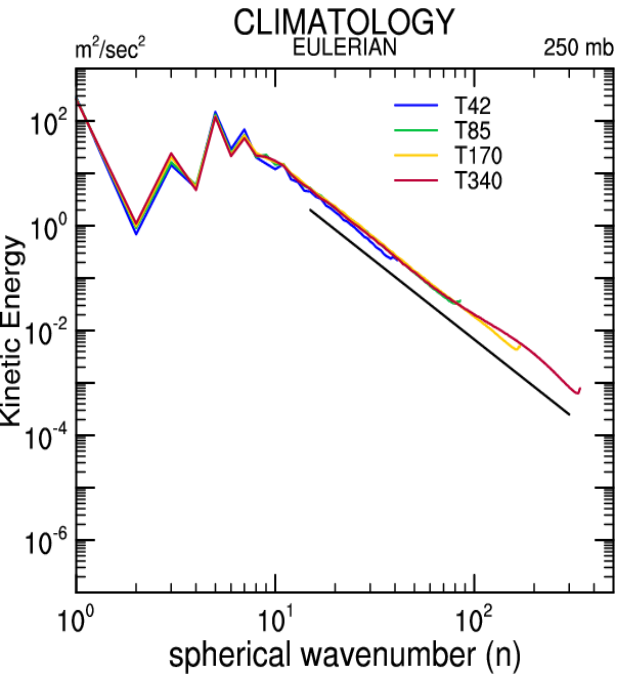


Summary

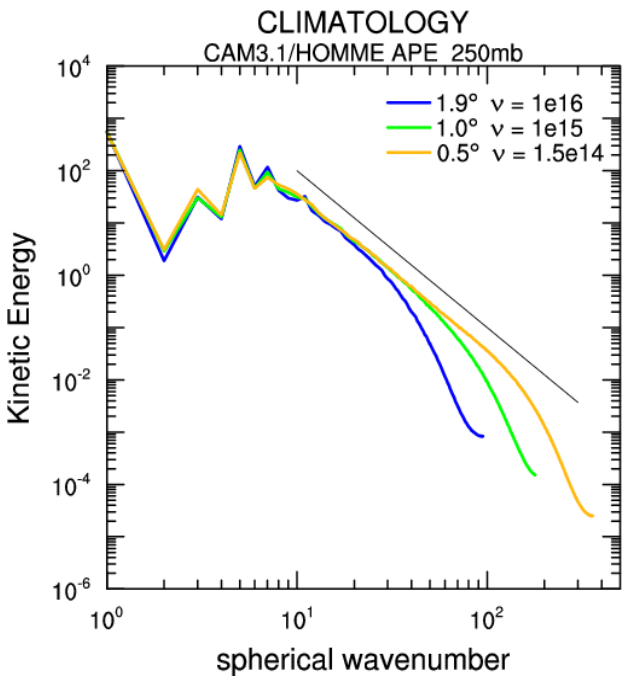
- **CAM**
  - Infrastructure can handle non-lat/lon grids
  - With a scalable dycore, CAM is petascale ready
- **CAM/HOMME**
  - Very reasonable aqua planet experiments
  - Low dissipation dynamics and high resolution captures Nastrom-Gage type transition at 0.125 degree
- **Current Work**
  - CCSM coupling with land, ocean and ice (Mariana Vertenstein, Tony Craig, Kate Evans)
  - Better advection schemes for HOMME (Ram Nair, Amik St.Cyr)

Aqua Planet Experiment: Comparison with FV & Eulerian Dycore

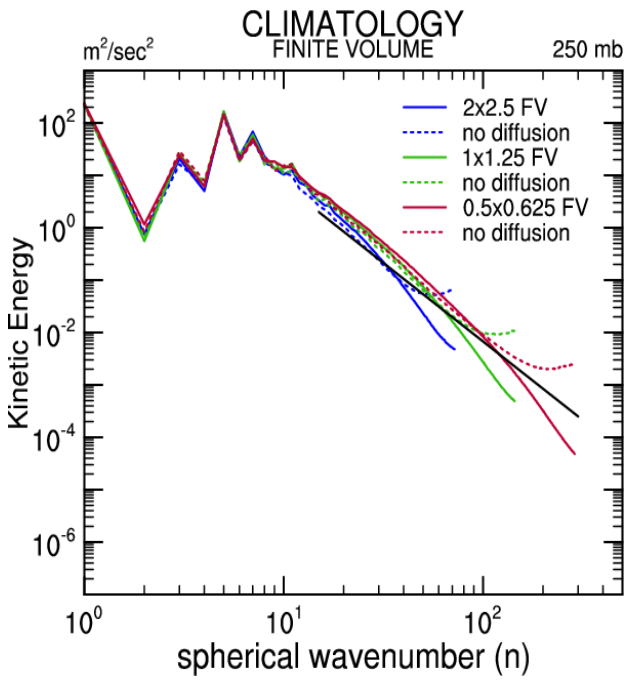
EULERIAN



HOMME



FV



Aqua Planet Experiment: Comparison with FV & Eulerian Dycore