An Overview of CCSM-HOMME and recent simulation results

Mark Taylor (Sandia), mataylo@sandia.gov

J. Edwards (NCAR/IBM), K. Evans (ORNL), A. Fournier (NCAR), P. Lauritzen (NCAR), A. St.Cyr (NCAR)

Acknowledgements:

CCSM Software Development Team (M. Vertenstein NCAR)

J. Hack (ORNL), J. Tribbia (NCAR), D. Williamson (NCAR)

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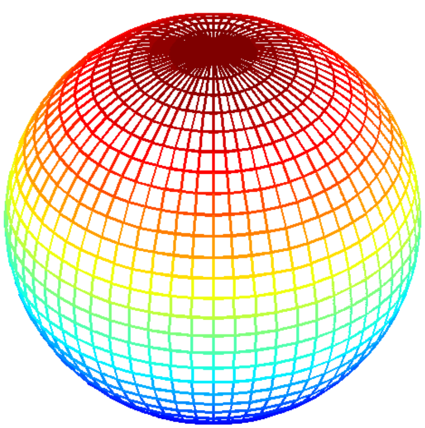
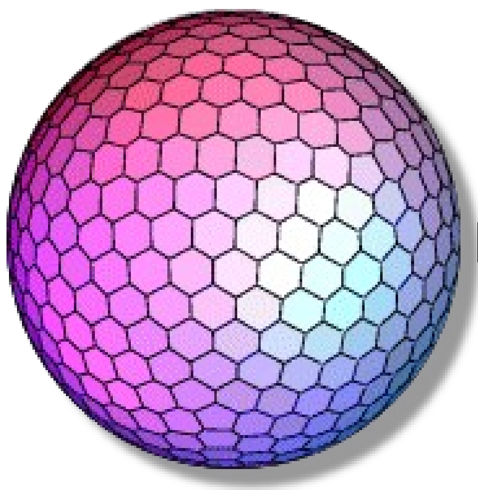
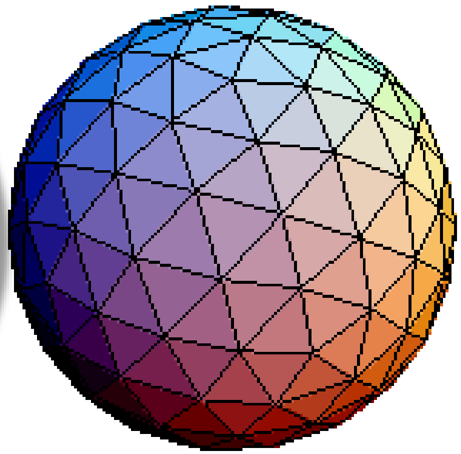
Outline

- **CCSM-HOMME: Integration of the HOMME (CG) dynamical core into the CCSM**
  - CCSM: NCAR Community Climate System Model
  - CAM: CCSM Atmospheric Component
  - HOMME: NCAR High-Order Method Modeling Environment. Contains several cubed-sphere based dycores (CG and DG), solves the shallow water equations or 3D primitive equations, with explicit, semi-implict and fully implicit timestepping methods and AMR.
  - Motivation: Improved scalability of the CCSM.



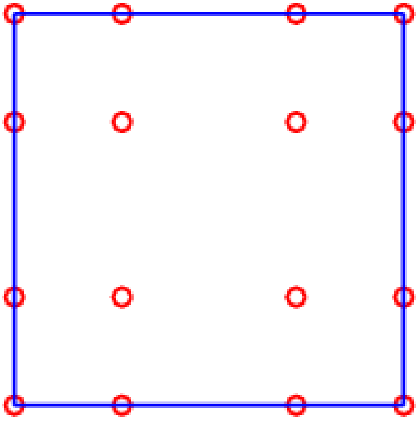



Main Results

- Real Planet Simulations (1 degree, 110km)
  - Perpetual year 2000 simulations with active land and data ocean/ice
  - "Track 1" configuration simulations starting to look pretty good as compared to T85 and FV 0.9x1.25.
  - Still some minor issues to track down
- Scalable CCSM:
  - CCSM-HOMME 1/8 degree (14km) running at 0.5 SYPD (atmosphere, land, data ocean/ice) on 56K processors.
  - Runs confirm that the scalability of the dynamical core is preserved by CAM, and the scalability of CAM is preserved by the CCSM.
  - Should scale to 340K processors (> 2.5 SYPD)
  - Subcycle dynamics/tracers: > 5 SYPD

CCSM-HOMME

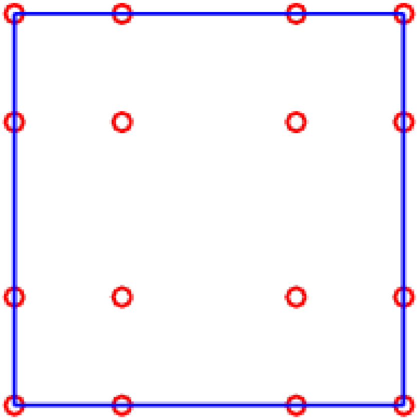
- Solves the three-dimensional hydrostatic primitive equations
- Spectral Elements: A continuous-Galerkin, *hp* finite element method. Cubed-sphere grid with p=3
- Horizontal Discretization: 4th order accurate and on arbitrary conforming unstructured grids
- Vertical Discretization: Simmons & Burridge MWR 1981 (centered finite differences) used for the dynamics, Lagrange+Remap (SJ Lin 2004, Zerroukat QJRMS 2005) used for tracers.
- Excellent Conservation: local conservation of mass, energy and PV (2D)



Local Conservation: Mass

- Relatively new result for finite elements:
  - Hughes et al. JCP 2000: *The Continuous Galerken Method is Locally Conservative*
  - Extended to inexact integration formulation with curvilinear elements (spectral elements): Taylor & Fournier 2009.
- Local conservation often obtained by replacing divergence operator by control volume flux. In FE, we use the numerical divergence operator directly and rely on the discrete form of the identity, for any element Ω :

$$\int_{\Omega} \nabla \cdot p\boldsymbol{v} = \oint_{\partial\Omega} p\boldsymbol{v} \cdot \hat{\boldsymbol{n}}$$



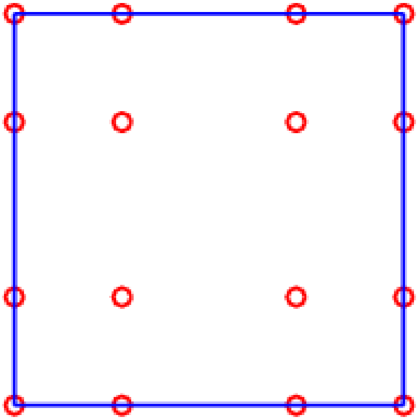
- Identity holds for any curvilinear conforming mesh
- Since p & v are continuous in a CG formulation, element edge flux is always continuous

Local Conservation: Energy

- Local conservation on energy is obtained by using the vector invariant formulation of the equations, combined with the FE discrete form of the integration by parts identity: for any element Ω :

$$\int_{\Omega} p \nabla \cdot \boldsymbol{v} + \int_{\Omega} \boldsymbol{v} \cdot \nabla p = \oint_{\partial \Omega} p \boldsymbol{v} \cdot \hat{\boldsymbol{n}}$$

- Energy conservation obtained by exact, term-by-term balance of all adiabatic terms in the KE, IE and PE budgets.
- Identity holds on any curvilinear conforming mesh
- Energy conservation is semi-discrete: exact with exact time integration.



PV conservation (2D shallow water)

Shallow water equations, vector invariant form:

$$\frac{\partial \boldsymbol{u}}{\partial t}+(\omega+f)\hat{\boldsymbol{k}}\times\boldsymbol{u}+\nabla\left(\frac{1}{2}\boldsymbol{u}^{2}+gH\right)=0$$

Using the FE discrete version of CURL GRAD = 0, we can show that for a solution u above, the *assembled* vorticity, omega-hat, defined by

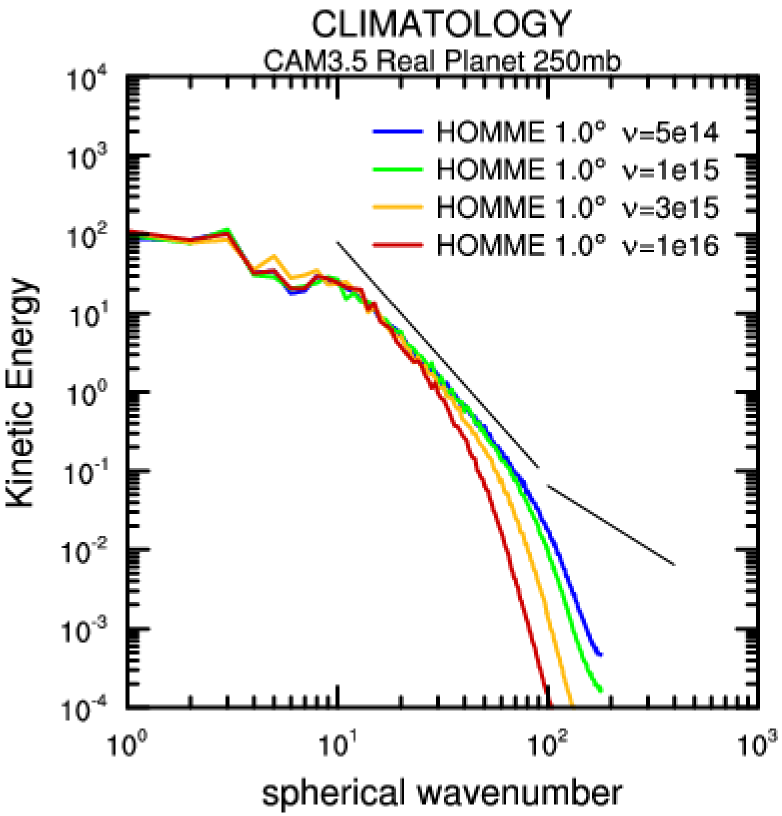
$$\int\phi\hat{\omega}=\int\phi\hat{\boldsymbol{k}}\cdot\nabla\times\boldsymbol{u}\qquad\forall\phi$$

satisfies the FE discretization of the conservation-form PV equation:

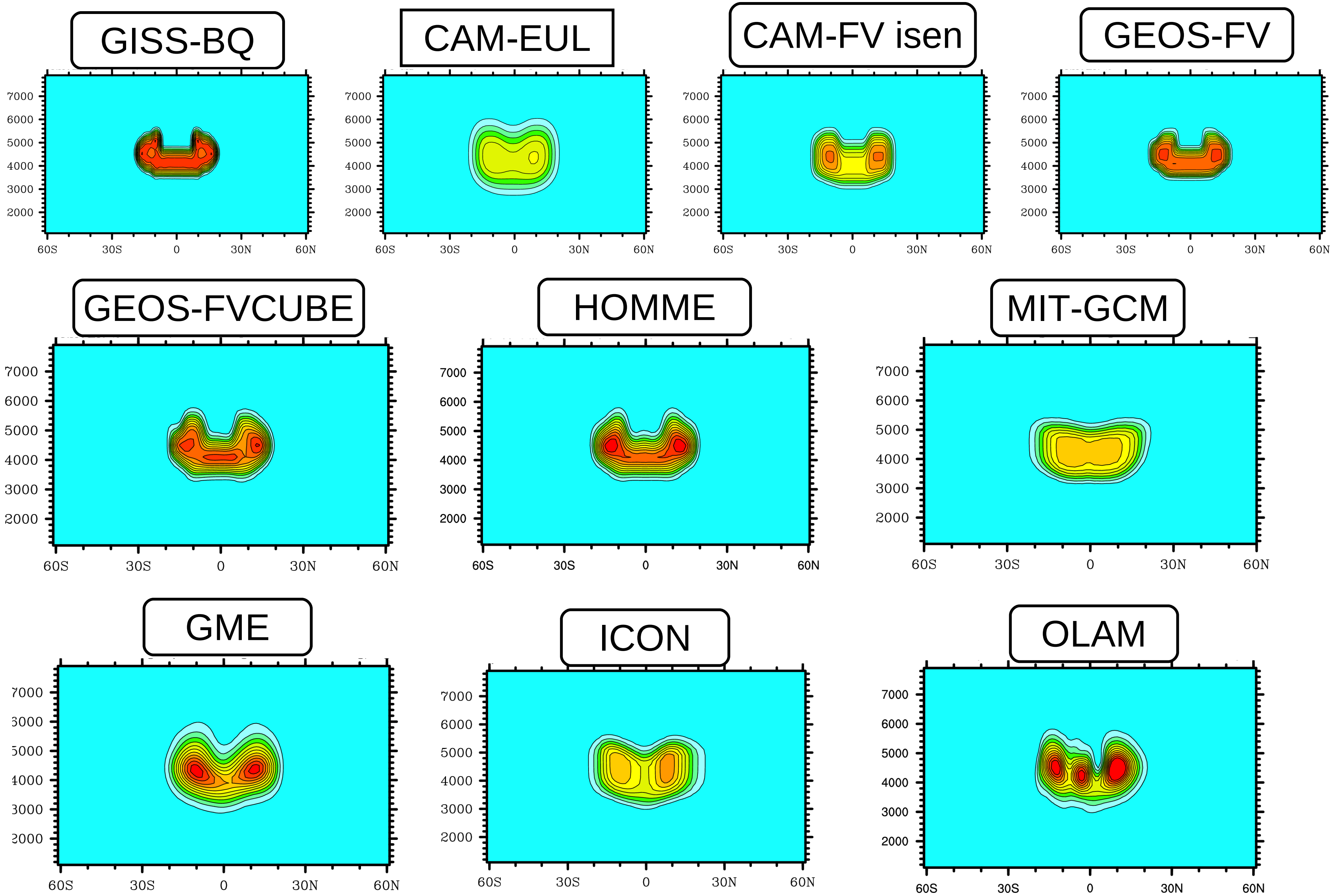
$$\frac{\partial}{\partial t}(\hat{\omega}+f)+\nabla\cdot(\hat{\omega}+f)\boldsymbol{u}=0$$

Dissipation

- At a typical 1 degree resolution: strong enstrophy cascade
- Dissipate enstrophy via dissipation of KE (1.5 W/m^2), similar to all other dycores in CAM
- HOMME uses an LES approach modeled after CAM-Eul: hyperviscosity (grad^4). KE dissipation exactly balanced by matching heating term to preserve TE.
- Other approaches include Implicit-LES (CAM-FV), where advection operator dissipates KE. TE conserved via fixer.

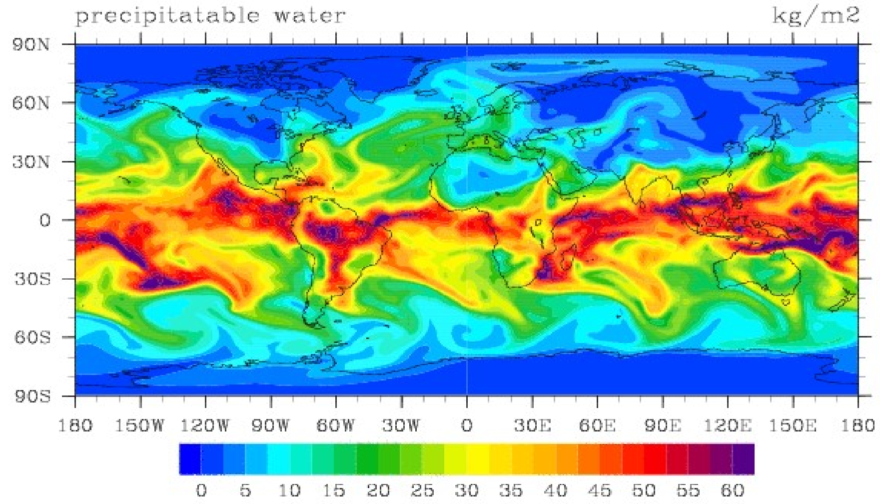


Advection Results from the NCAR 2008 ASP Coloquium Dynamical Core Experiment



Real Planet Simulations
1.0 Degree (112km)

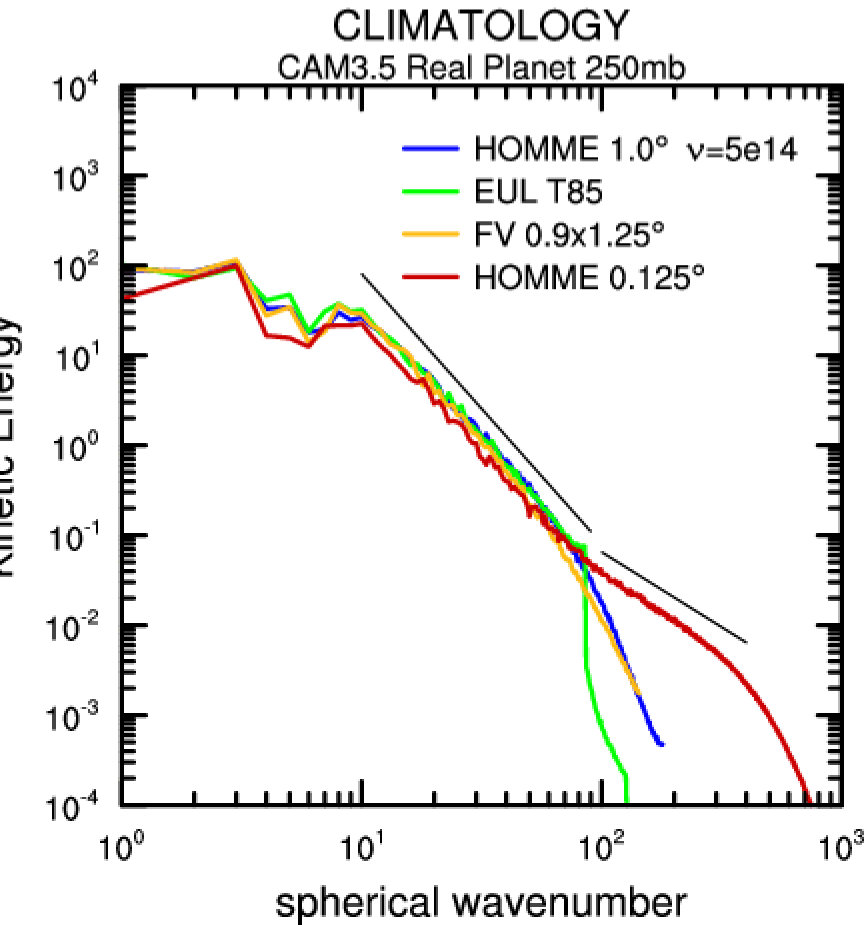
- CCSM4 beta 16, “-phys cam3_5_1”, cyclical year 2000, 5 year simulations
- CCSM “Tri-Grid” infrastructure:
  – CAM-HOMME on cubed-sphere grid (1 degree)
  – CLM2 on FV 1.9x2.5
  – Data ocean/ice on gx1v4
- H. Wang et al. MWR 2007: CAM2-SEAM with CAM2 land model running on cubed-sphere grid.

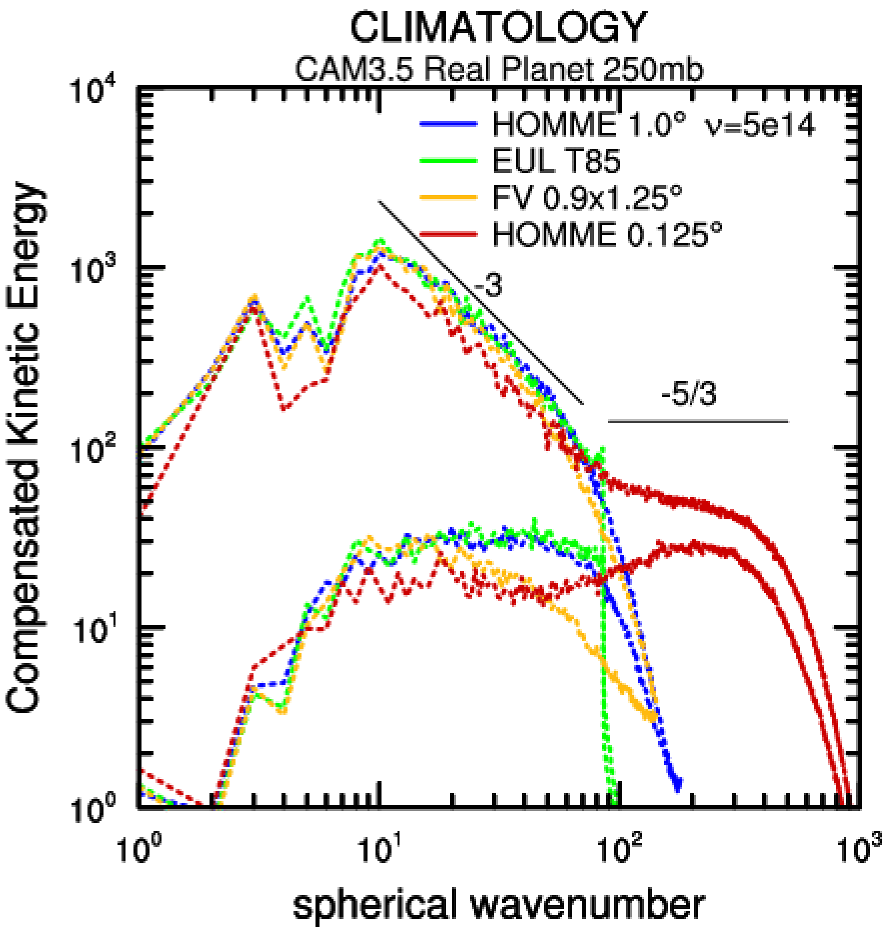


Global Means

	EUL-T85	HOMME 1.0	FV 0.9x1.25
RESTOM	1.517	1.403	1.325
RESSURF	1.512	1.405	1.362
CLDHGH	25.6	22.8	23.8
CLDMED	16.8	15.2	16.5
CLDLOW	34.6	34.9	31.5
EKE-850mb	40.3	39.6	36.7
EP	-1.2E-04	-9.7E-04	-9.0E-05

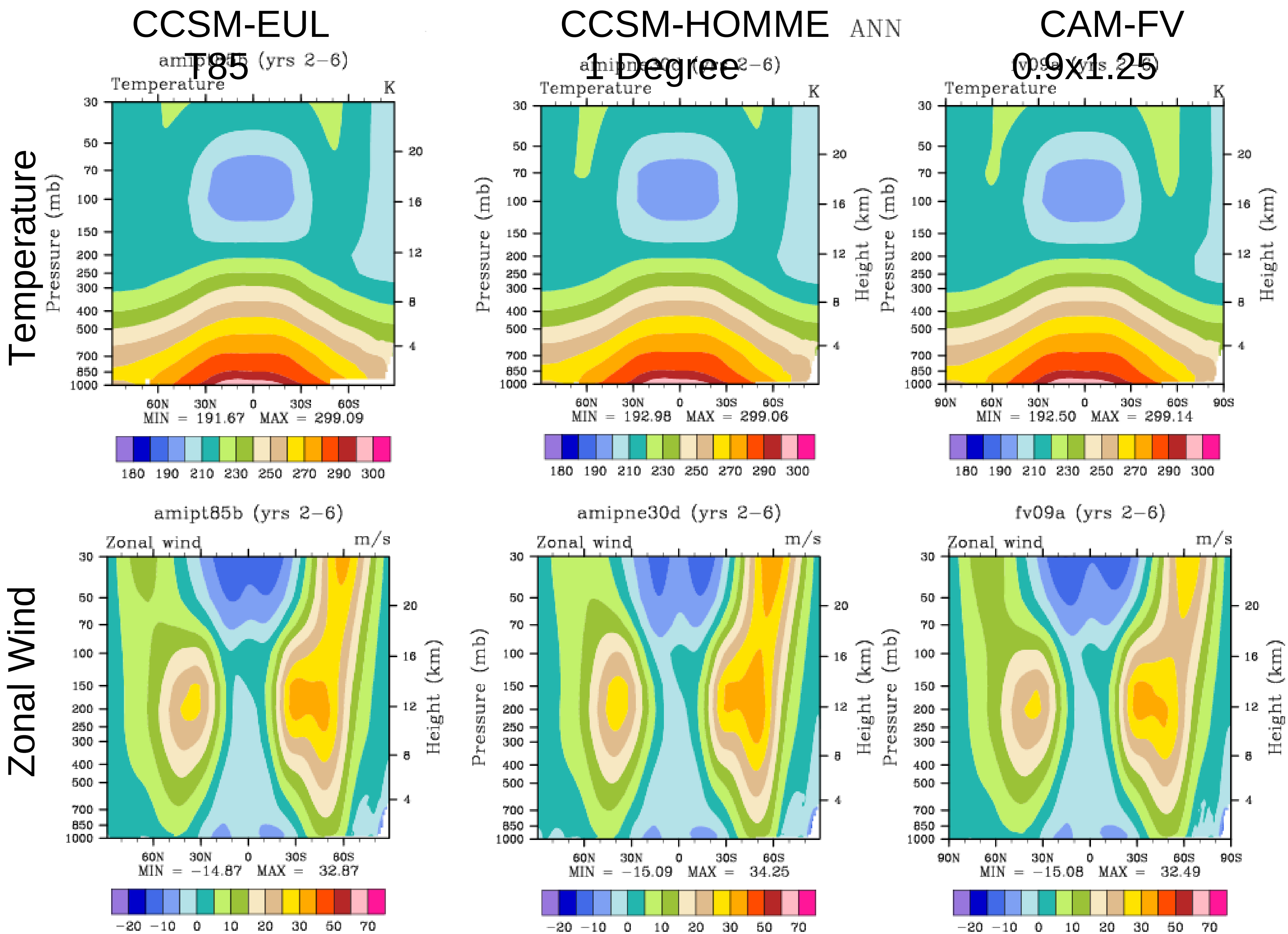
Real Planet: KE spectra





Rotational (top) and compressible (bottom) components

Real Planet: Zonal Means (Annual)

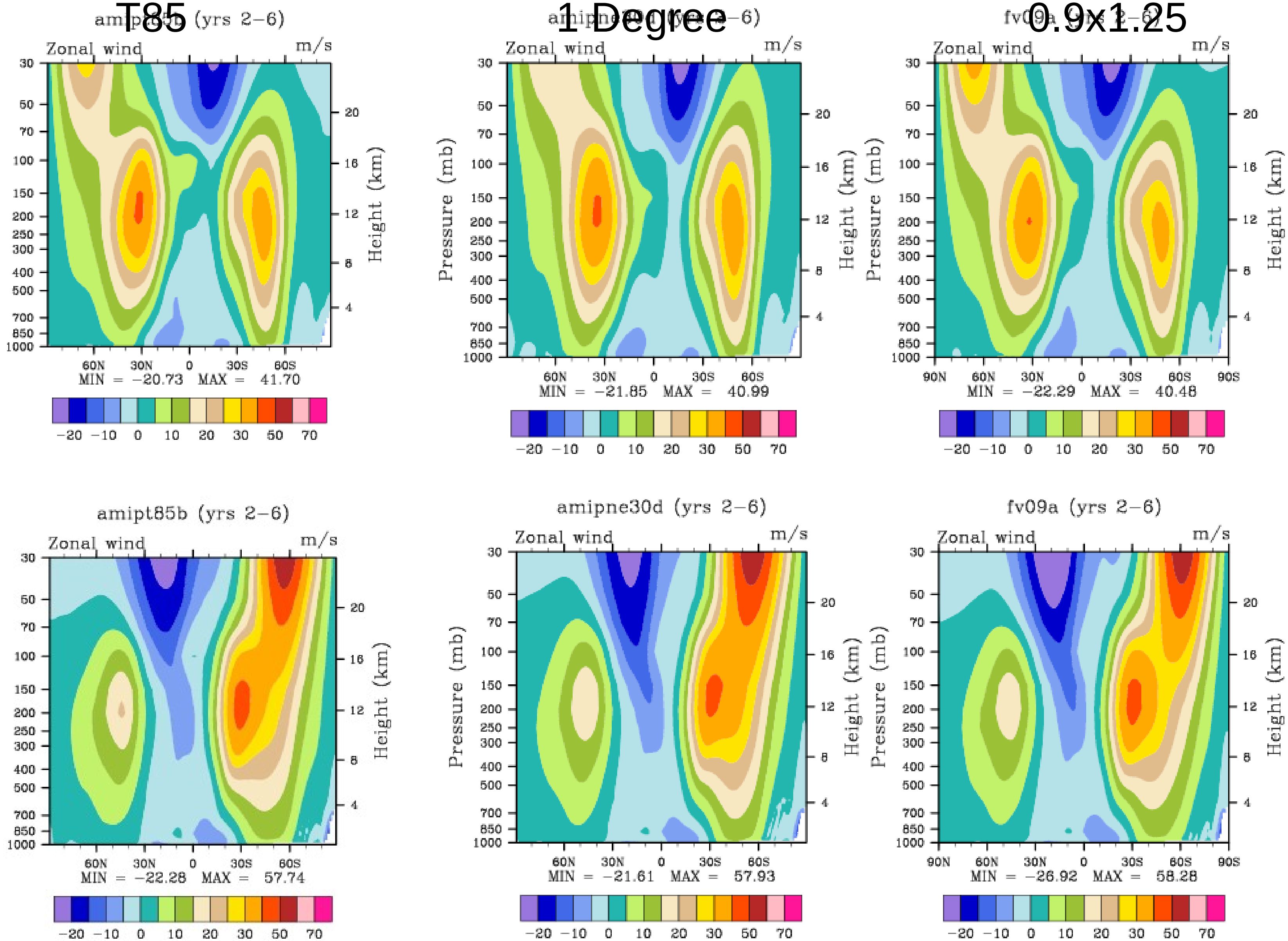


Real Planet: Zonal Means (DFJ, JJA)

CCSM-EUL T85 | CCSM-HOMME 1 Degree | CAM-FV 0.9x1.25

Zonal Wind DJF

Zonal Wind JJA

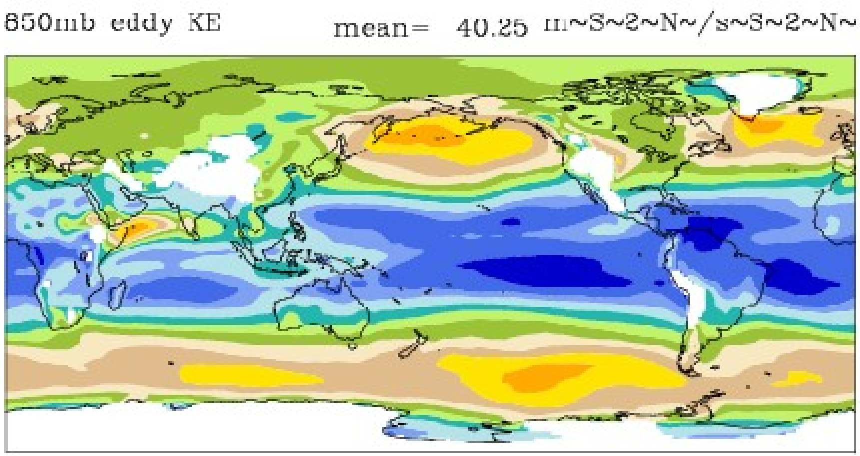


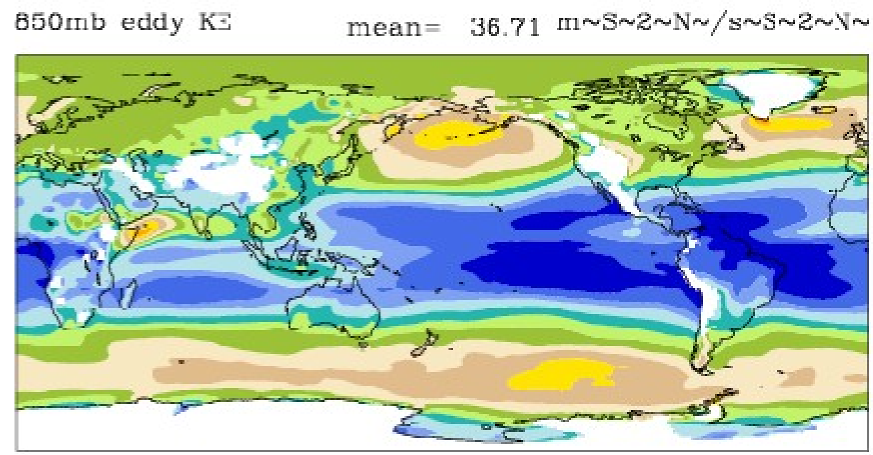
Eddy Kinetic Energy 850mb

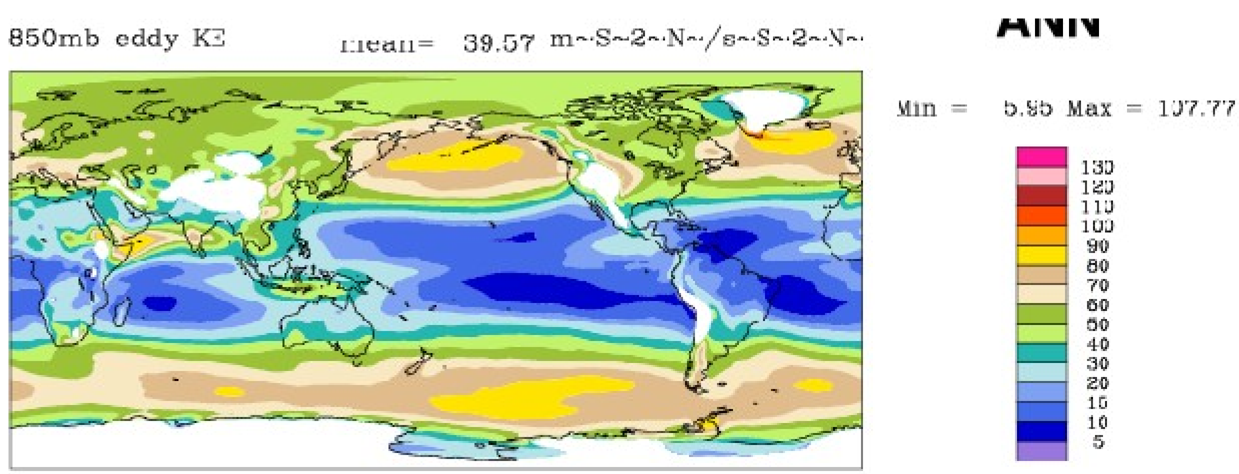
CCSM-EUL
T85

CCSM-HOMME
1 Degree

CAM-FV
0.9x1.25





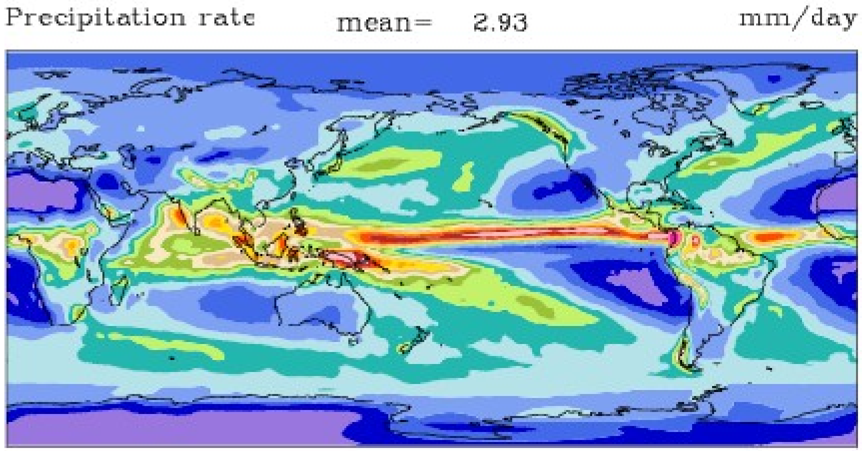


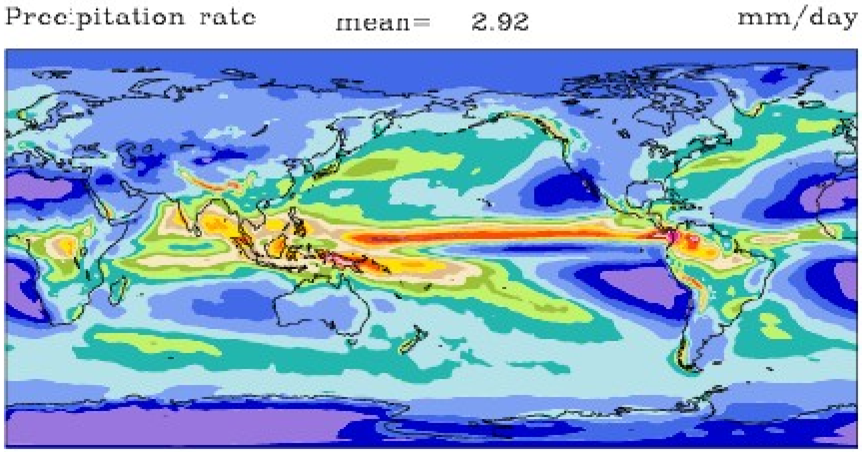
Precipitation Rate

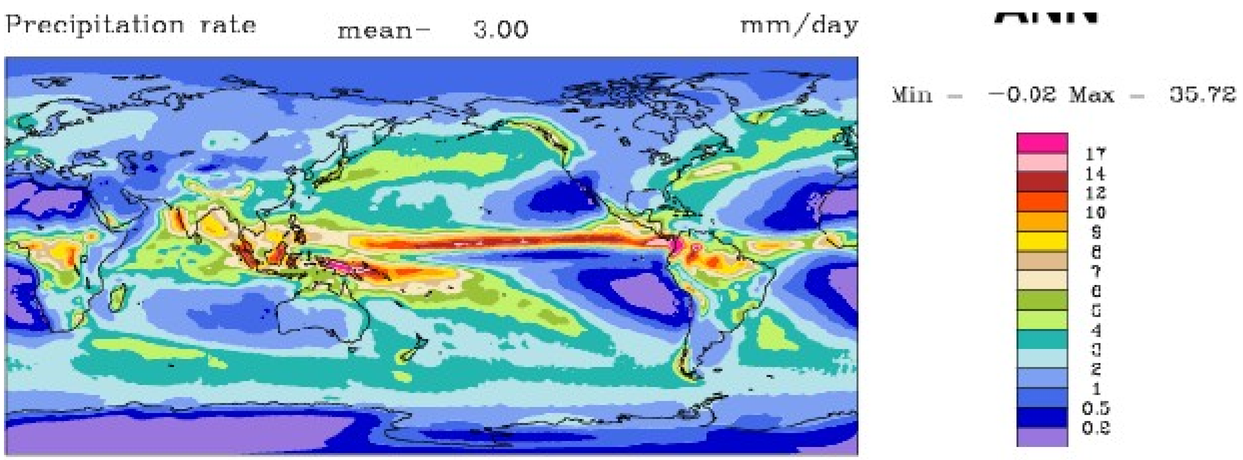
CCSM-EUL
T85

CCSM-HOMME
1 Degree

CAM-FV
0.9x1.25





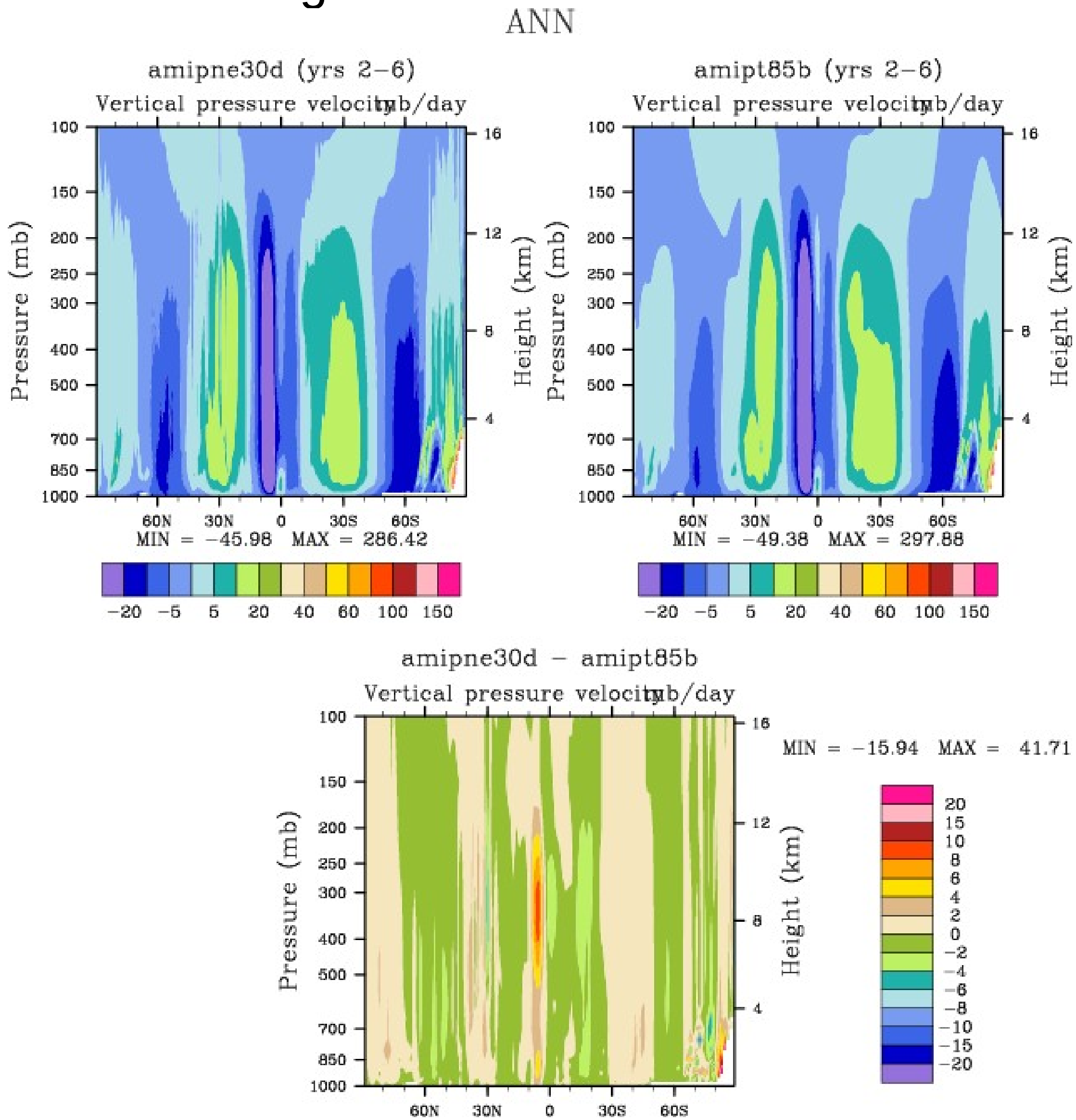


Precipitation: Detailed analysis being performed by Saroj Mishra (NCAR), preliminary results 2009 CCSM Workshop poster

Vertical Pressure Velocity

CCSM-HOMME
1 Degree

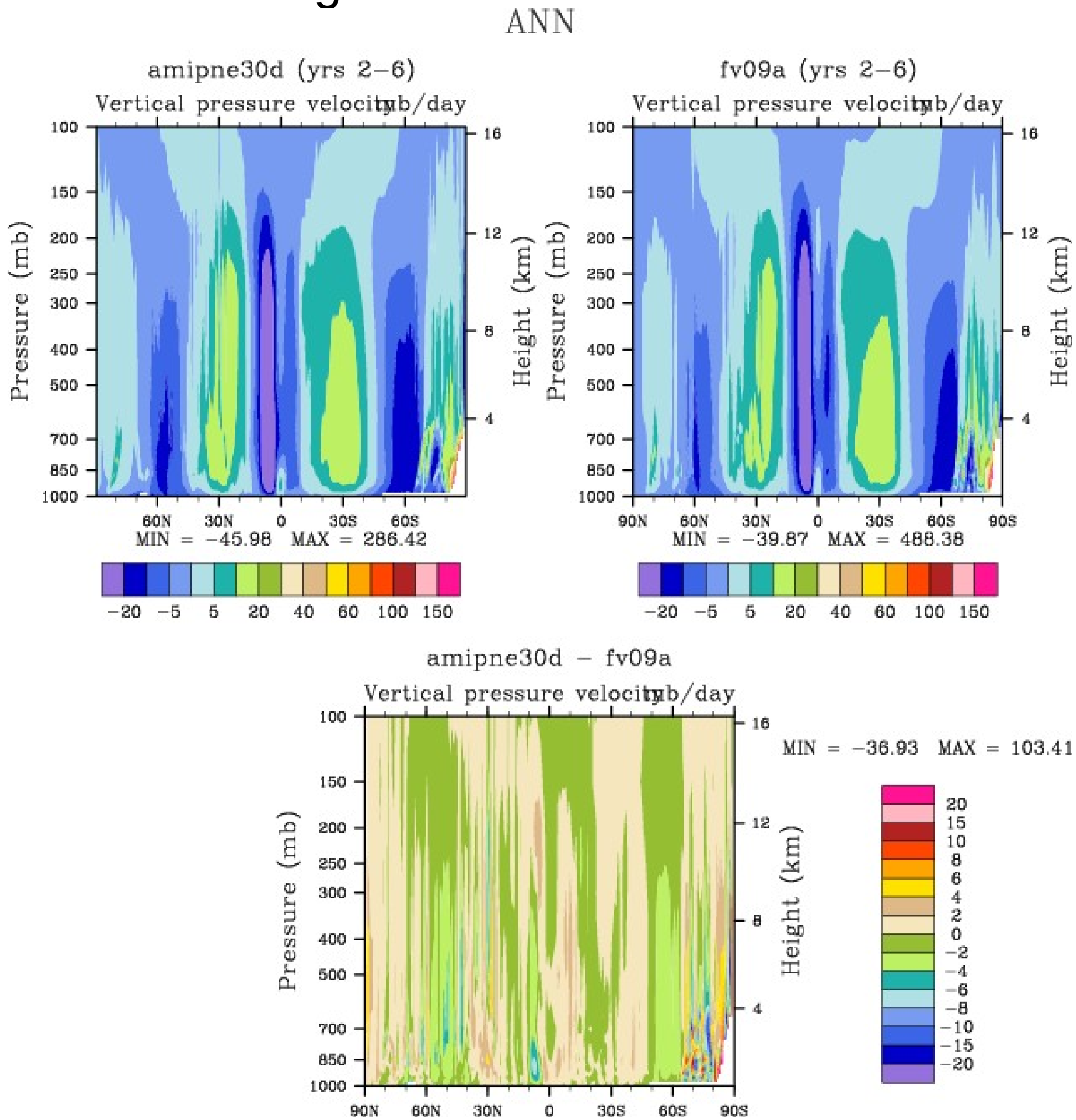
CCSM-EUL
T85



Vertical Pressure Velocity

CCSM-HOMME 1 Degree

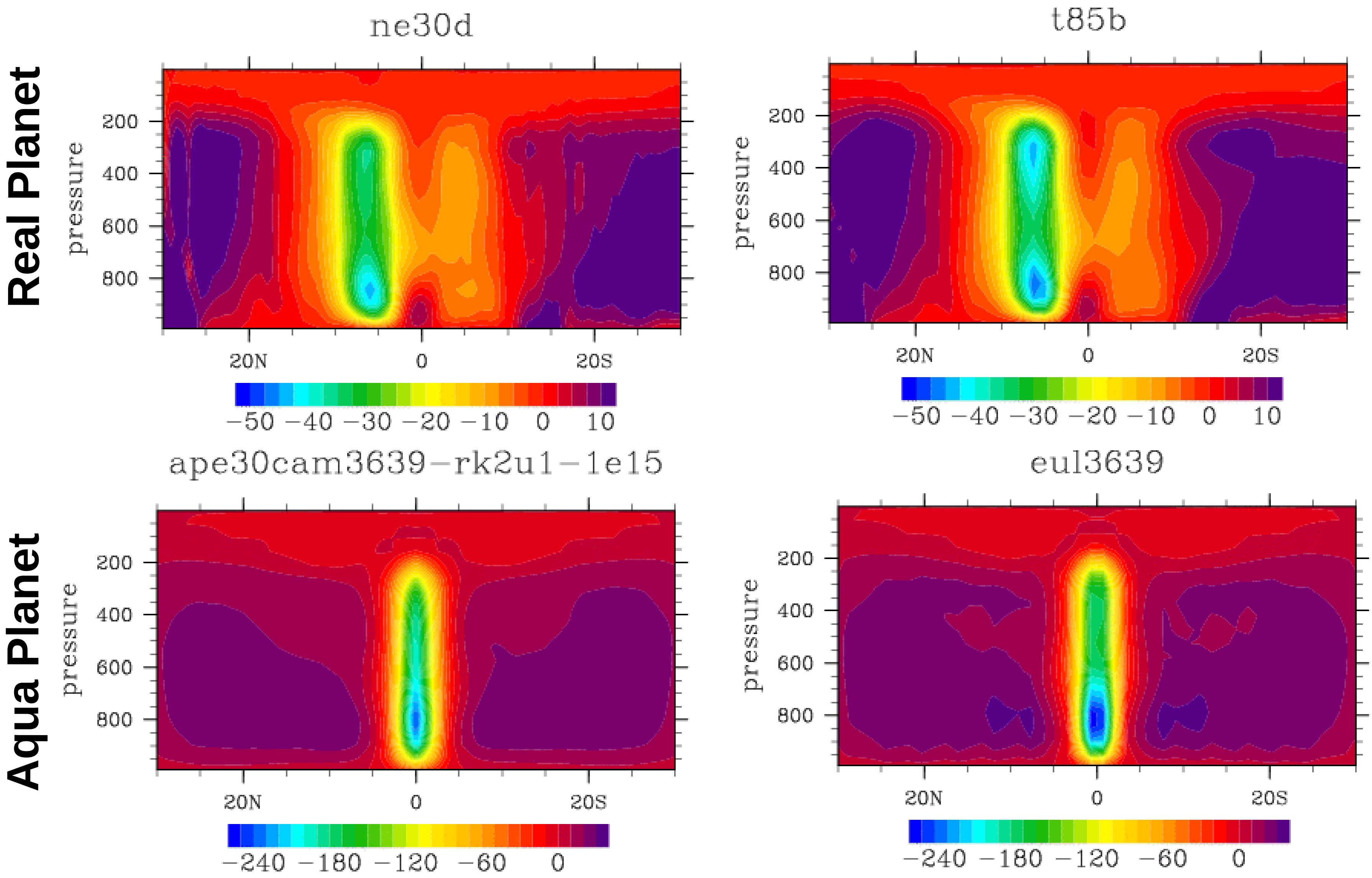
CAM FV 0.9x1.25



Vertical Pressure Velocity

CCSM-HOMME
1 Degree

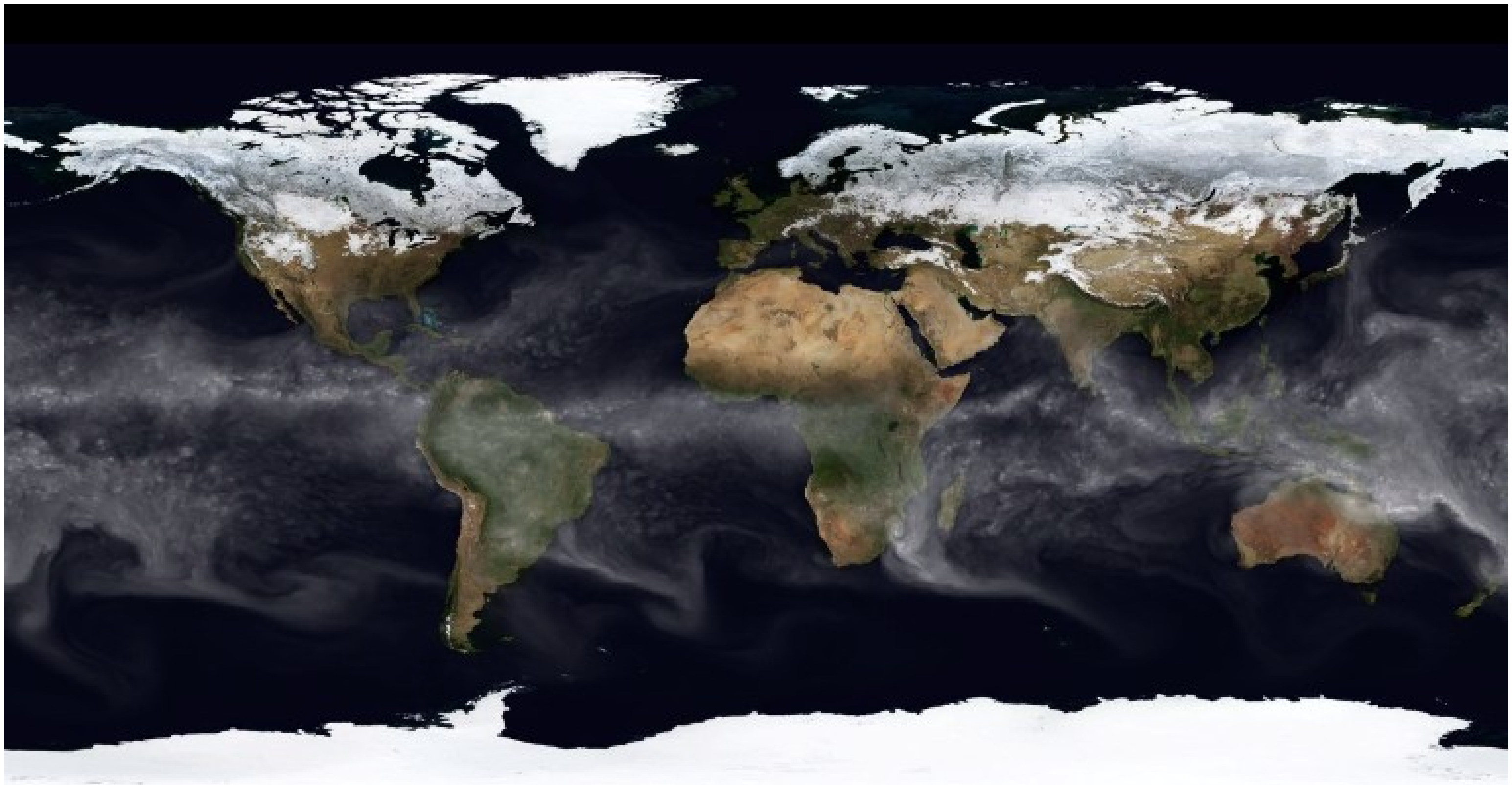
CCSM-EUL
T85



Real Planet: 1/8 Degree Simulations

- CCSM4 beta 16, Track 1 “-phys cam3_5_1” configuration
  - Cyclical year 2000 data sets
  - CAM-HOMME 1/8 degree, 56,000 cores
  - CLM2 on FV ¼ degree, 1024 cores
  - Data ocean/ice, gx1v5, 512 cores
  - Coupler, 512 cores
- BG/P Simulations:
  - Full history, plus 2h snapshots of some flow variables
  - PIO/PNETCDF: history & restart ~700 MB/s
  - LLNL system: 1.5 year simulation completed in 3 days (0.52 SYPD)

Precipitable Water Animation, Dec-Jan



Animation: Jamison Daniel (ORNL)

Sandia National Laboratories

Conclusions

- CCSM infrastructure supports ultra-high resolution
  - On track to obtain > 5 SYPD at 1/8 degree
- CCSM-HOMME
  - Excellent Local Conservation (mass, energy, PV-2D)
  - Competitive advection operator
  - A few more issues to track down in 1.0 degree simulations, followed by AMIP simulations for submission to PCMDI.