The Spectral Element Dynamical Core in the CESM

Mark Taylor

Sandia National Labs

mataylo@sandia.gov

J. Edwards (NCAR), K. Evans (ORNL), O. Guba (Sandia), P. Lauritzen (NCAR), M. Levy (Sandia), A. Mirin (LLNL), S. Mishra (NCAR), R. Neale (NCAR), J. Tribbia (NCAR), P. Worley (ORNL)

CESM PI Meeting, Washington D.C., Sept. 29, 2011

U.S. Department of Energy

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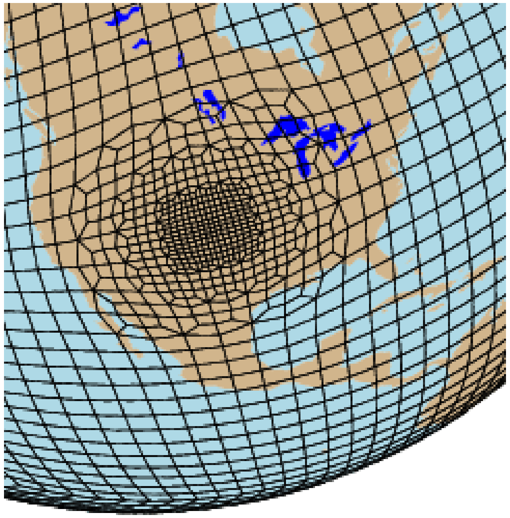
Outline

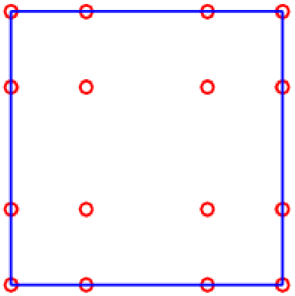
- CAM-SE:
  - CAM with HOMME's Spectral Element dynamical core
- Latest scalability results
- CAM4 and CAM5 AMIP results

CAM-SE in CESM
Status

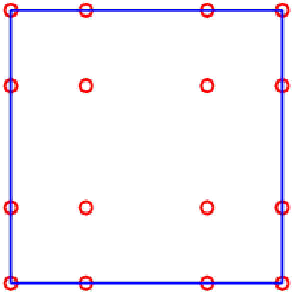
- CESM includes CAM4 F2000 configurations at 1° and 1/8° resolutions
- Currently running CAM5 AMIP and fully coupled simulations (not quite out-of-the-box)
- **Locally conserves mass, tracer mass and energy**
  - Change in energy ~0.002 W/m^2 without fixer
- Latest CAM trunk includes support for variable resolution meshes

Spectral Element Method





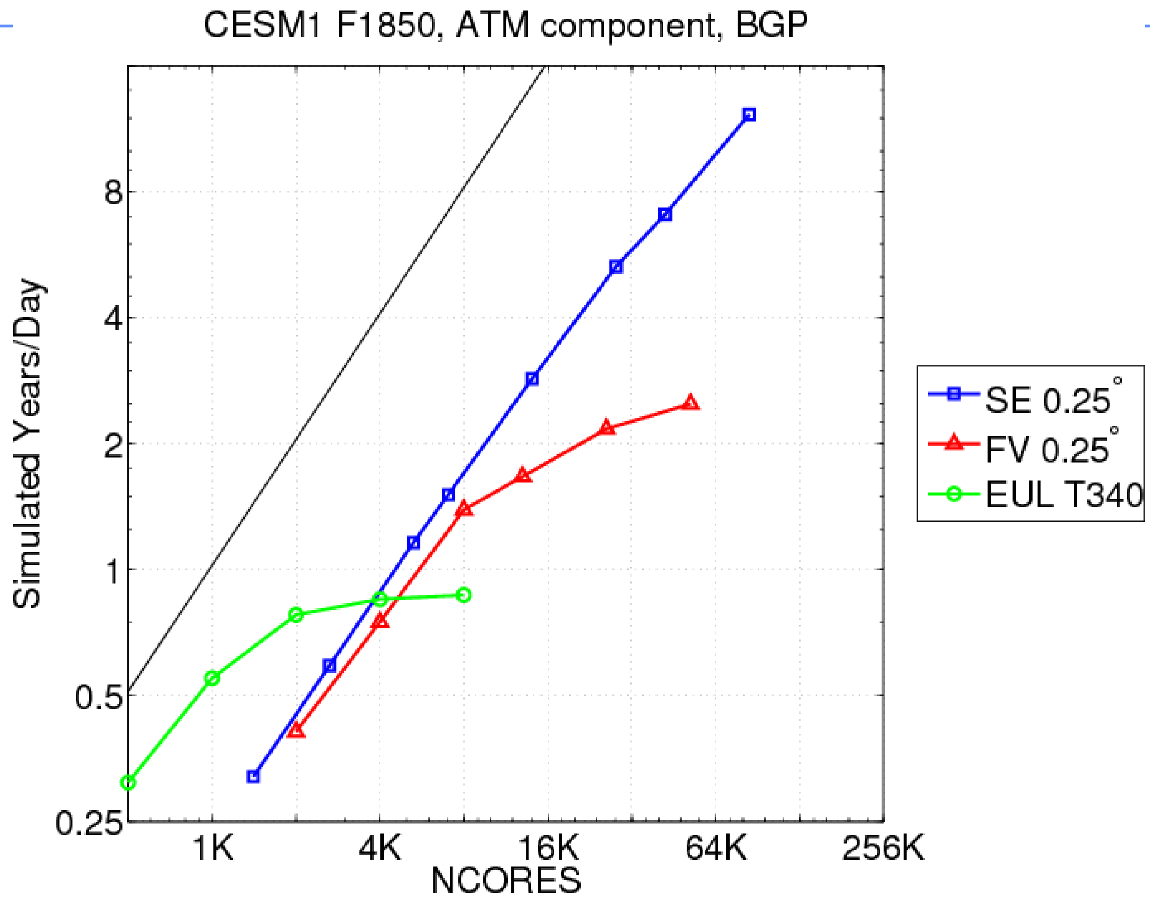
- Spectral Elements: A Continuous Galerkin Finite Element Method
  - Uses finite element grids made of quadrilateral elements
  - Galerkin formulation, with a Gauss-Lobatto quadrature based inner-product
  - Basis/test functions: degree *d* polynomials within each element, continuous across elements



Galerkin FE Approach Ideal for Modern Architectures

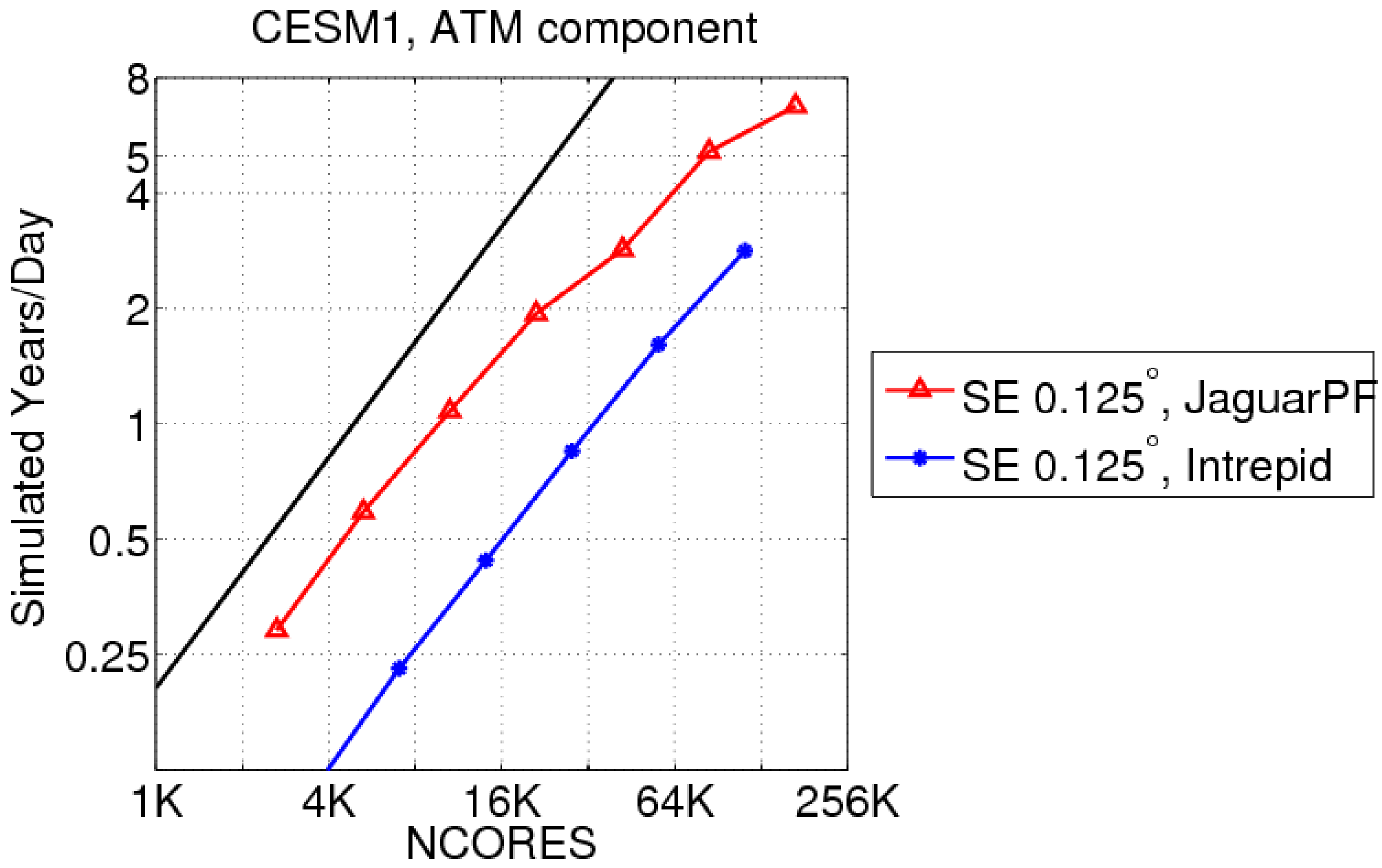
- Galerkin formulation of the equations leads to a 2 step solution procedure:
  - Step 1: All computations local to each element and on a tensor-product grid. Structured data with simple access patterns and arithmetically intensive operations: Extremely efficient on modern CPUs or GPUs
  - Step 2: Apply inverse mass matrix (projection operator).
- 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.
  - Gordon Bell Awards: 2000 (best performance, NEK5000), 2001 (honorable mention, HOMME) , 2003 (best performance, SPECFEM3D)

CAM4 Scalability, ANL Intrepid ¼° (28km)



- Compare CAM with SE, FV and EUL (global spectral) dycores
- CAM-SE achieves near perfect scalability to 1 element per core (86,000 cores). Peak performance: 12.2 SYPD.
- Atmosphere only times. Full CESM runs ~50% slower because of other components

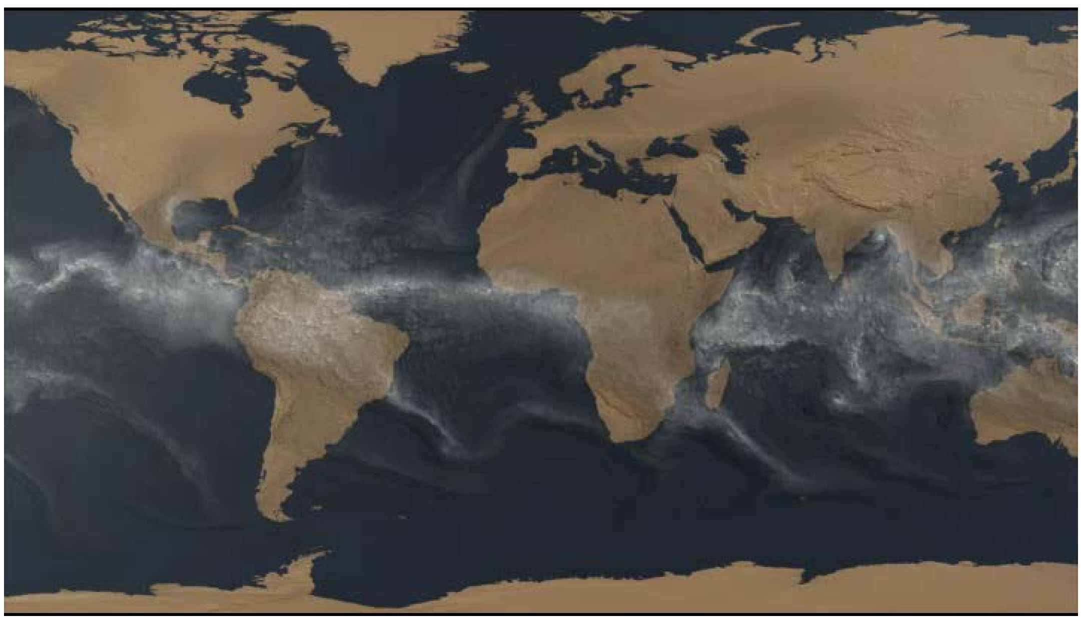
CAM-SE Scalability
Intrepid and JaguarPF   1/8° degree (14km)



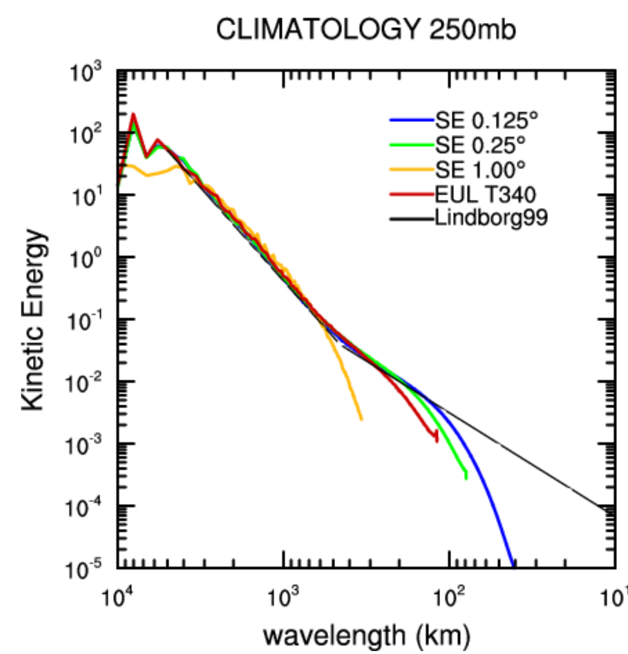
- Excellent scaling to near full machine on both LCFs:
- Intrepid (4 cores/node):   Excellent scalability, peak performance at 115K cores, 3 elements per core, 2.8 SYPD.
- JaguarPF (12 cores/node): Good scalability, peak performance at 172,800 cores (2 elements per core), 6.8 SYPD.

CAM4 1/8° (14km) Simulations

- CAM-SE 1/8° runs quickly and efficiently including I/O
- Excellent tropical cyclone activity
- Excellent KE spectra, with well captured -5/3 regime
- CAM4 climate suffers from physics resolution sensitivity issues.



Tropical cyclone activity at 1/8° resolution. Precipitable water animation from two months (Dec, Jan) of a 1 year simulation.

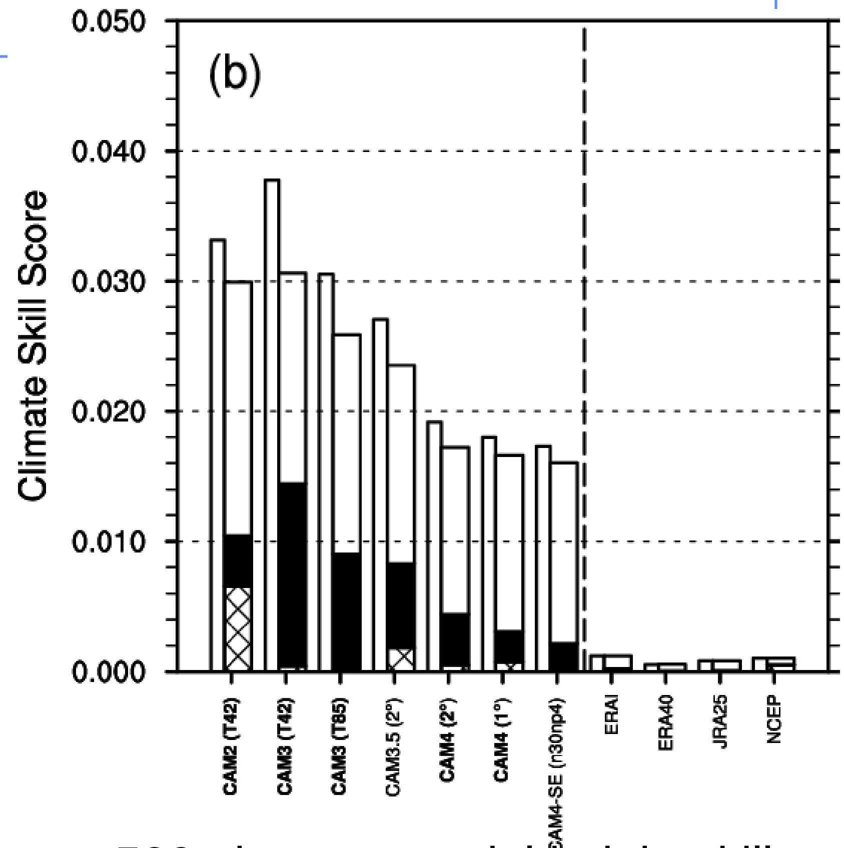


1/8° required to capture the -5/3 regime assocated with mesoscale variability

CAM4 1° AMIP Simulations

	RMSE	Bias
CAM 3.5	1.000	1.000
CAM4 SE	0.920	0.839
CAM4 FV	0.937	0.905

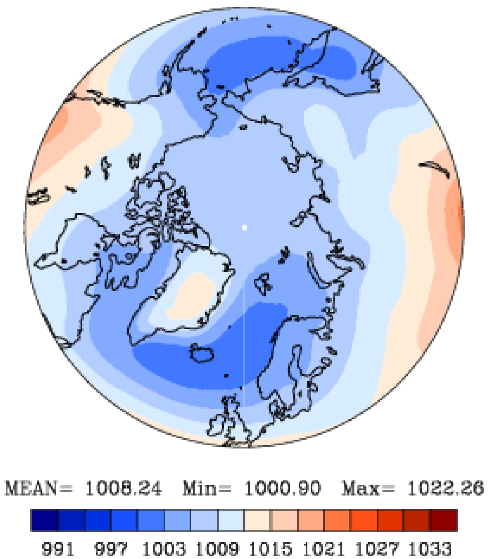
- K. Taylor diagram RMSE and Bias from CAM AMWG diagnostics
- CAM4-SE Simulation (Evans et al. under review JOC)



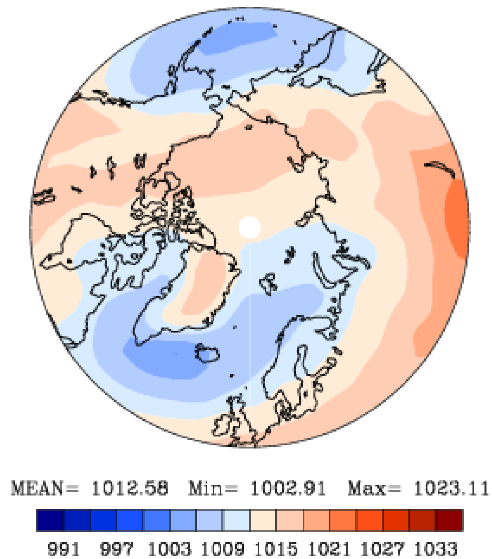
- 500mb geopotential height skill score (30-90N) DJF
- Mean square error from uncond. bias, cond. bias and phase error
- Source: Rich Neale (NCAR)

Sea Level Pressure

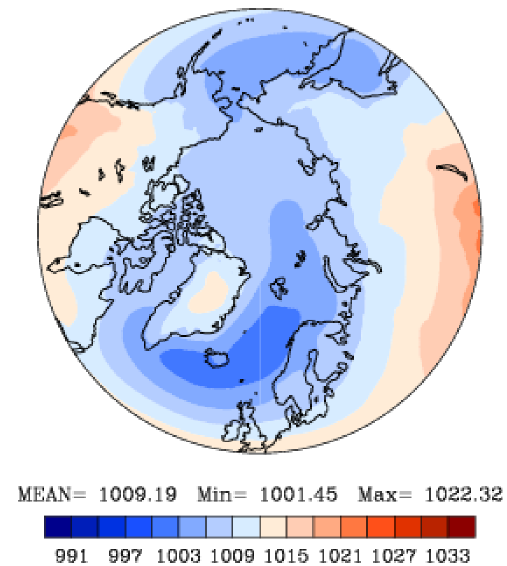
CAM4-SE 1°



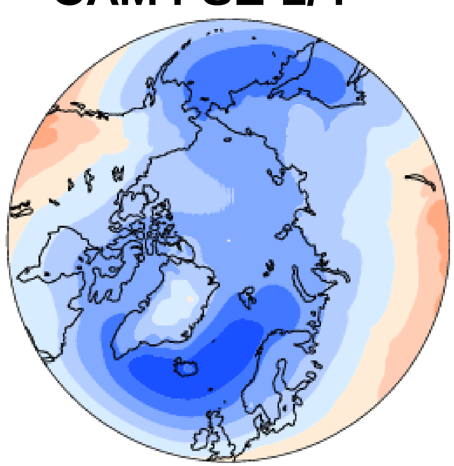
NCEP



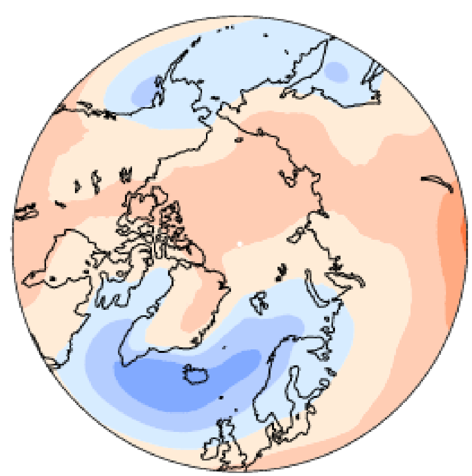
CAM4-FV 1°



CAM4-SE 1/4°



CAM5-SE 1°



CAM has too strong of an Icelandic low, in both SE and FV

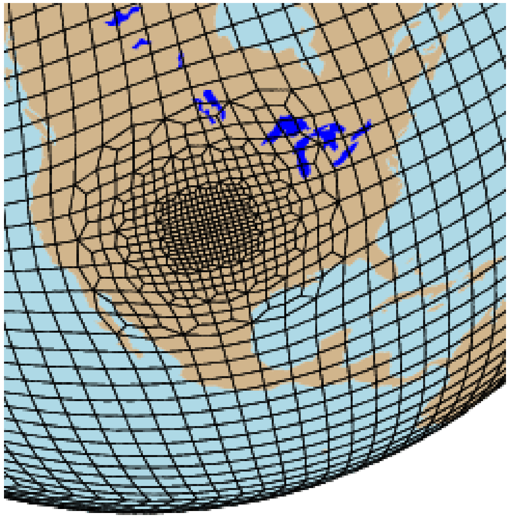
Icelandic low intensifies under mesh refinement, but is much improved with CAM5 physics

Future Plans

- Support CSSEF project goal of developing a global high-resolution CESM, calibrated and with quantified uncertainty.
- Developing CAM-SE configurations with CAM5 physics with variable resolution: 1° global, transitioning to 1/8° over ARM sites, for efficient calibration of the global 1/8° model.

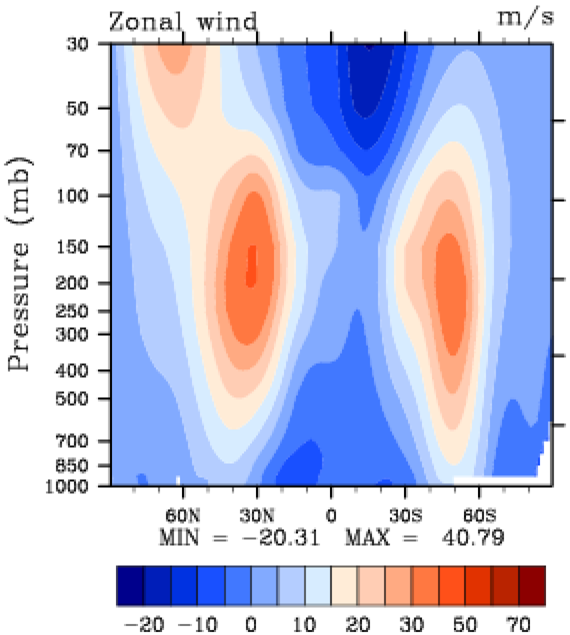
Spectral Element Method

- High-order (4^{th}) discretization
- Mimetic/compatible numerics:
  - Discretization preserves adjoint properties of div, grad and curl operators
  - Discrete versions (element level) of Stokes and Divergence theorem
  - Result: excellent local conservation, even for equations not written in conservation form: mass, energy, 2D PV.
- All properties preserved on fully unstructured grids

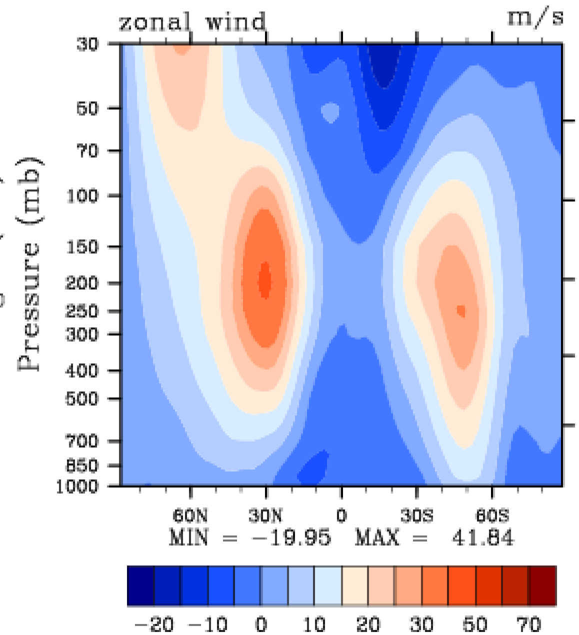


Zonal Mean Zonal Wind (DJF)

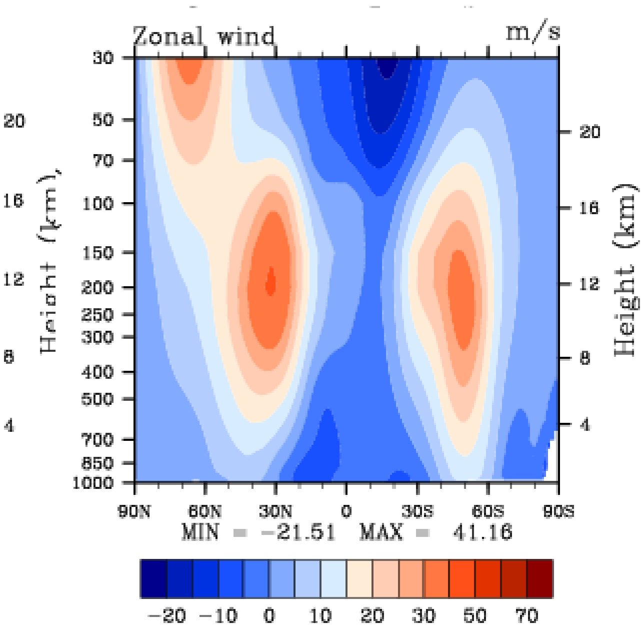
CAM4-SE 1°

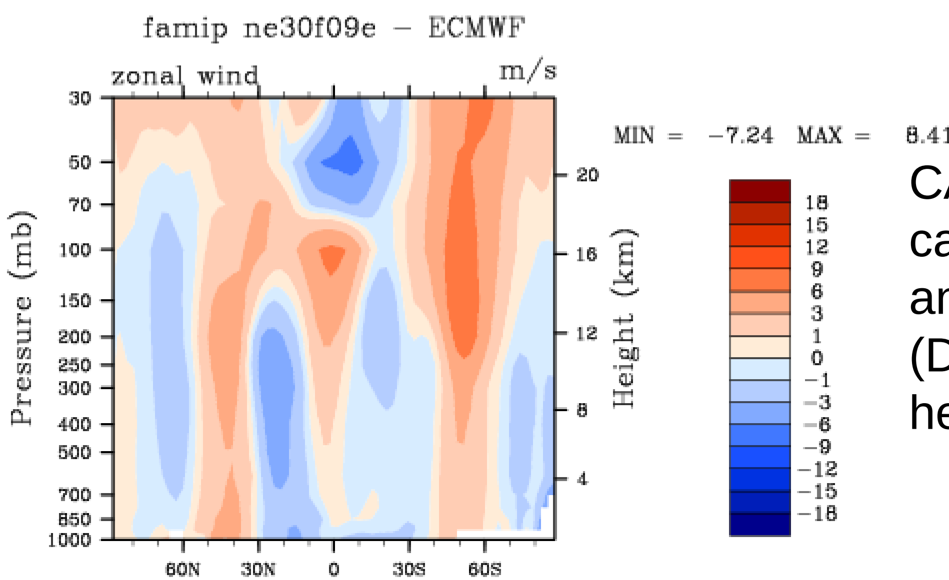


ECMWF



CAM4-FV 1°

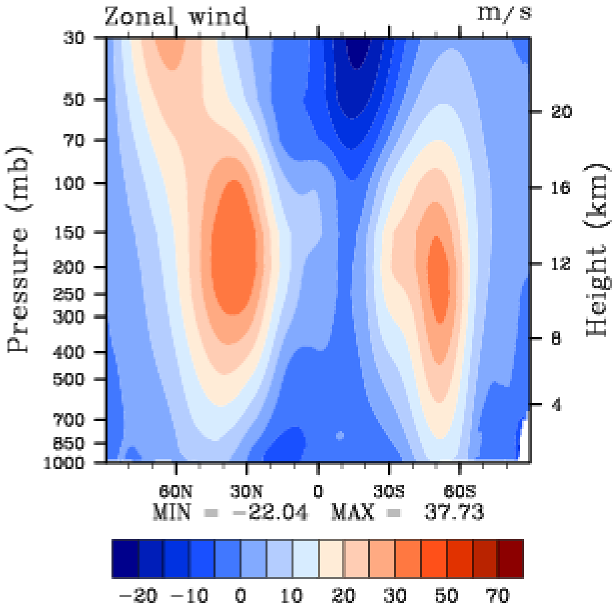




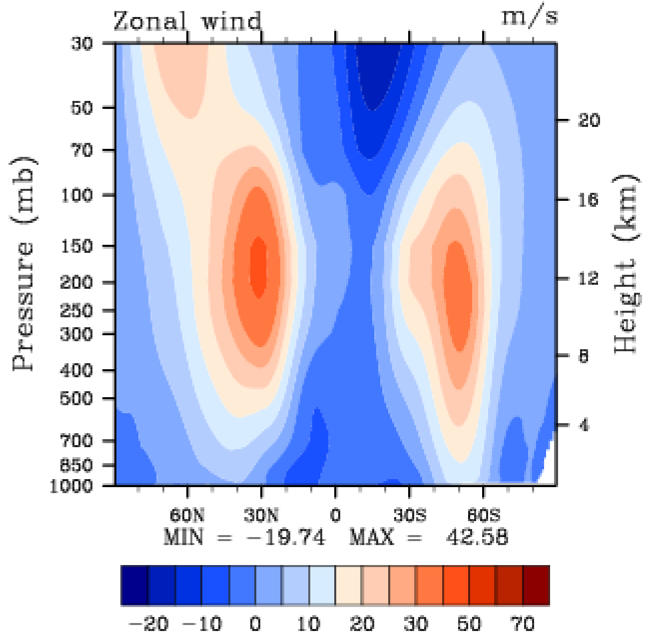
CAM does a good job capturing the southern (JJA) and northern hemisphere (DJF) polar jets. FV northern hemisphere jet is too strong

Zonal Mean Zonal Wind (DJF)

CAM4-SE 0.25°



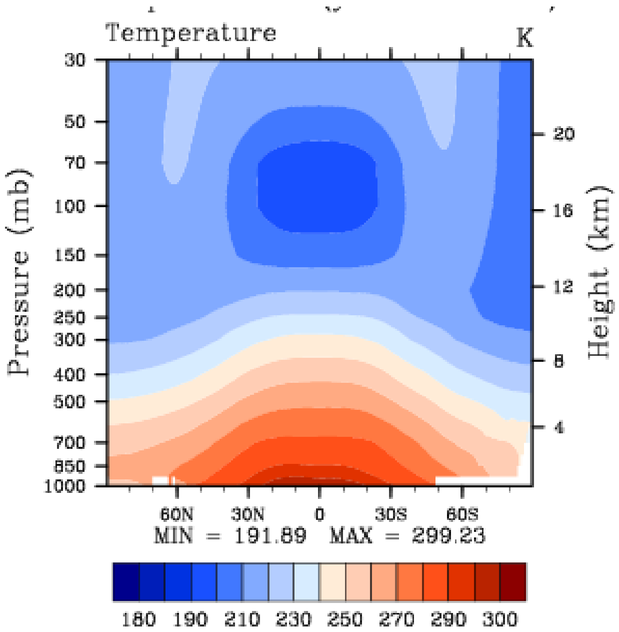
CAM5-SE 1°



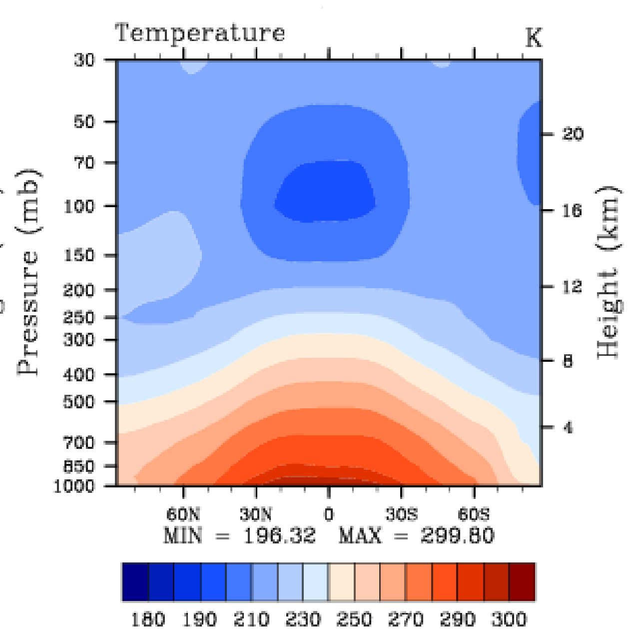
CAM-SE retains good polar jets at high resolution and with CAM5 physics

Zonal Mean Temperature

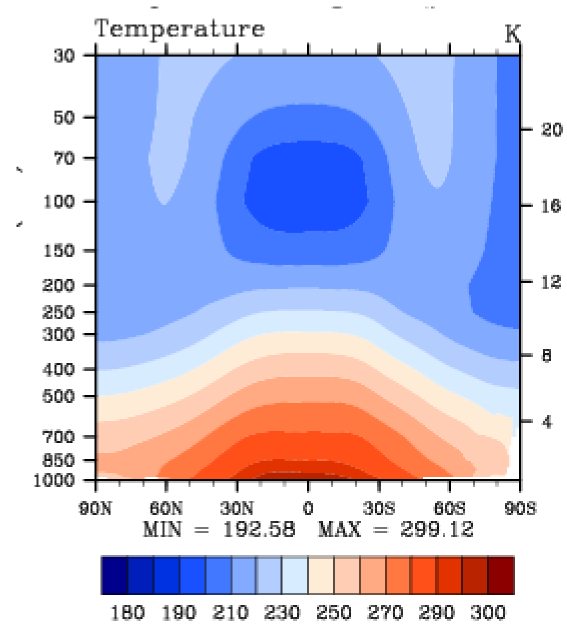
CAM4-SE 1°

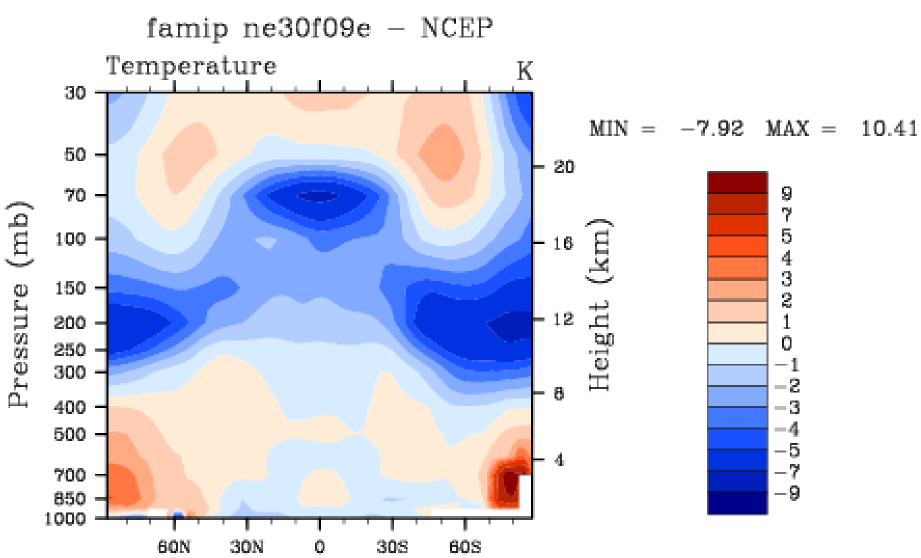


NCEP



CAM4-FV 1°

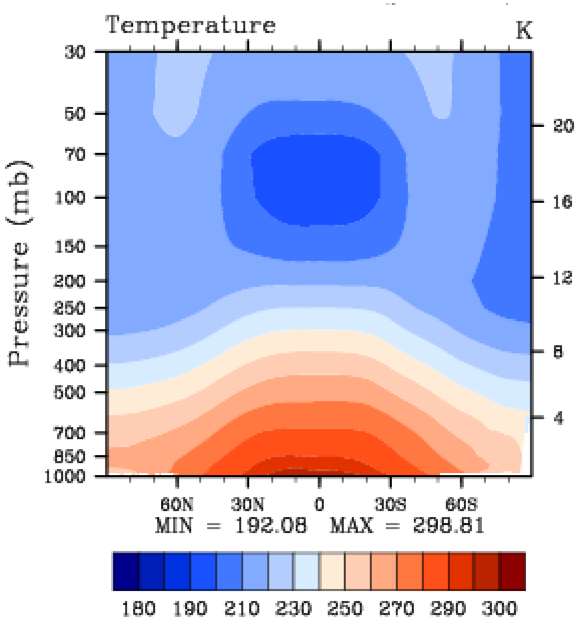




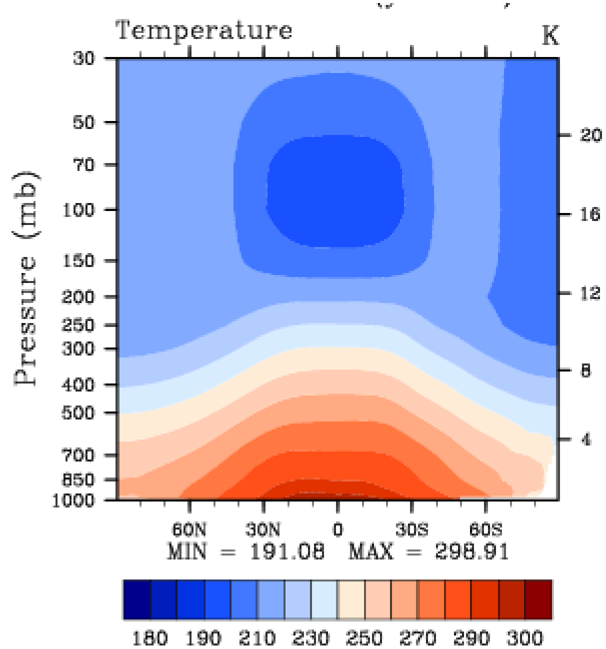
CAM has a long standing 200mb cold bias at the poles (both SE and FV)

Zonal Mean Temperature

CAM4-SE 0.25°



CAM5-SE 1°



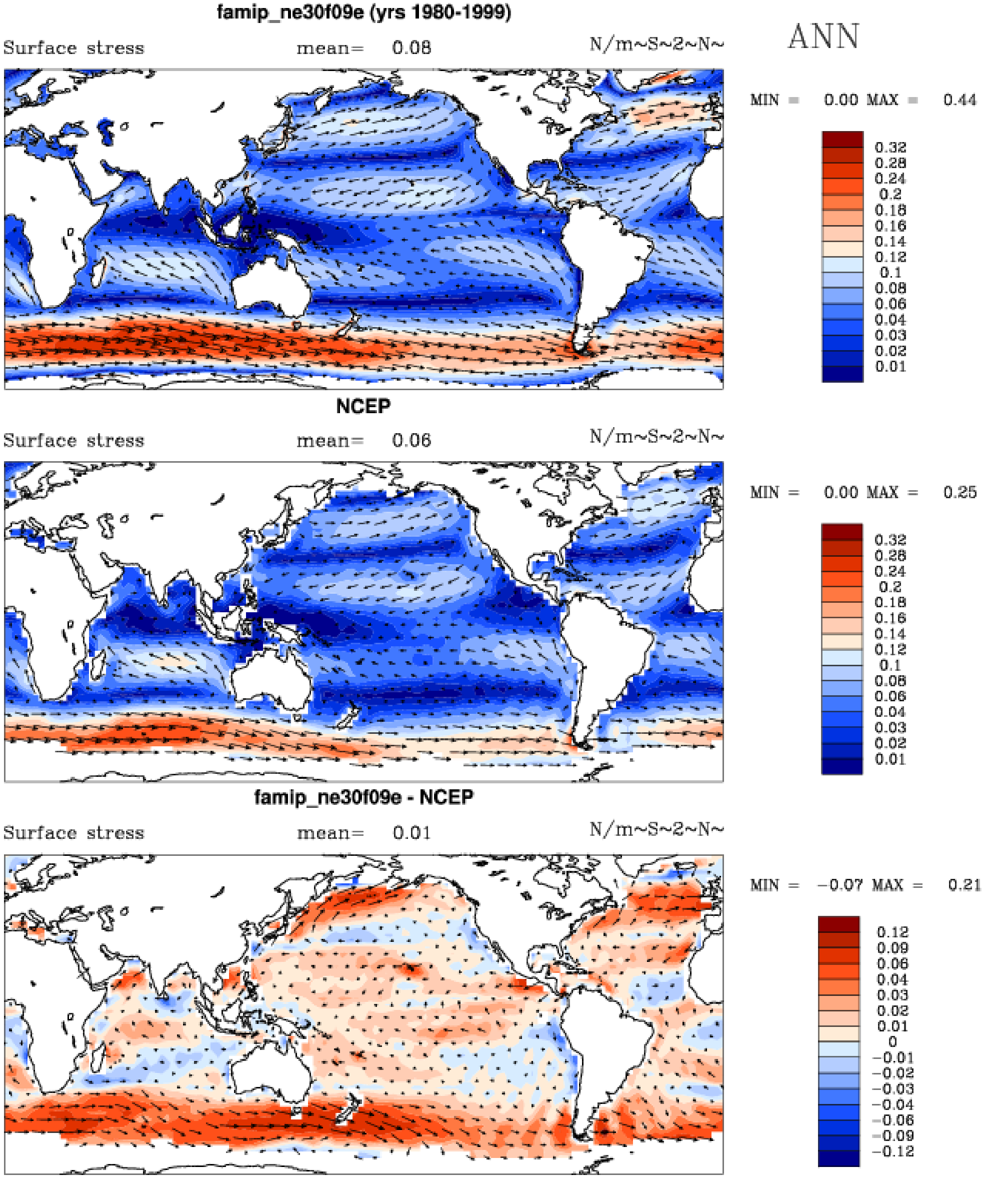
Result is insensitive to increasing resolution (left) or CAM5 physics (right)

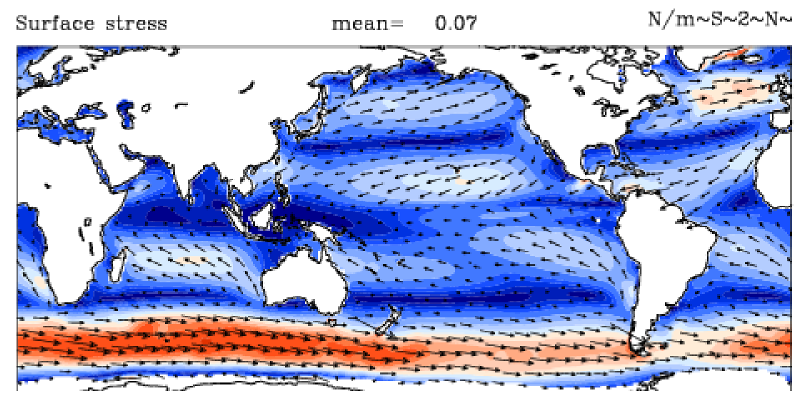
Surface Wind Stress (ocean)

CAM4-SE 1°

CAM4-FV 1°

NCEP

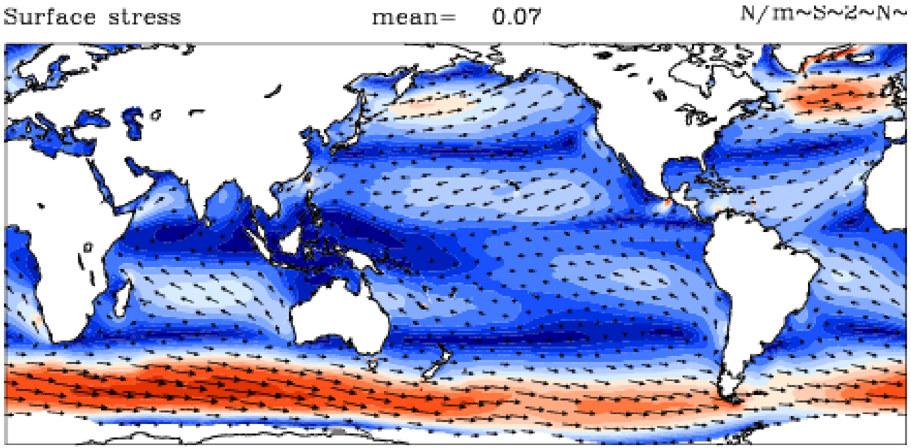




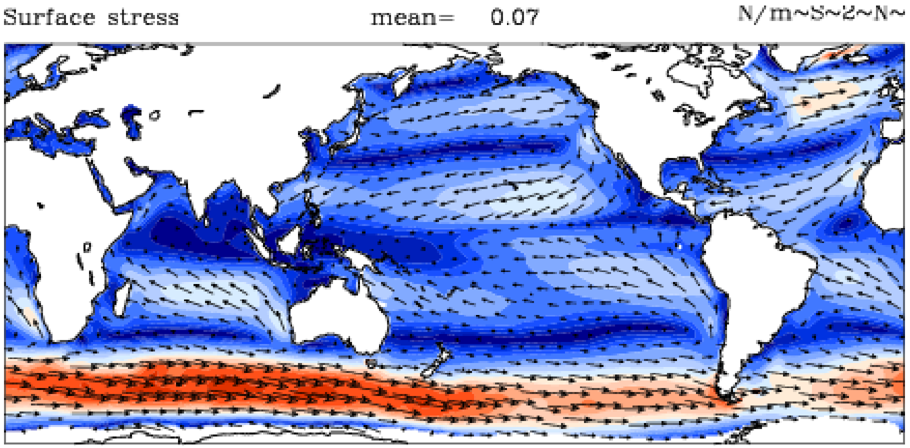
CAM wind stress is too strong (SE stronger than FV)

Surface Wind Stress (ocean)

CAM4-SE 0.25°



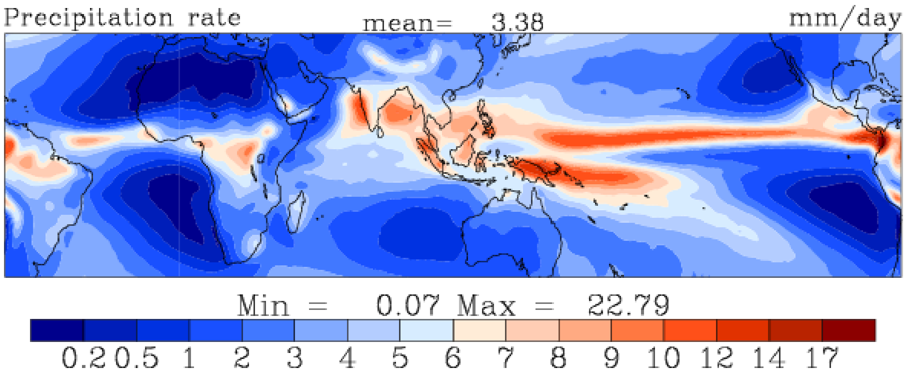
CAM5-SE 1°



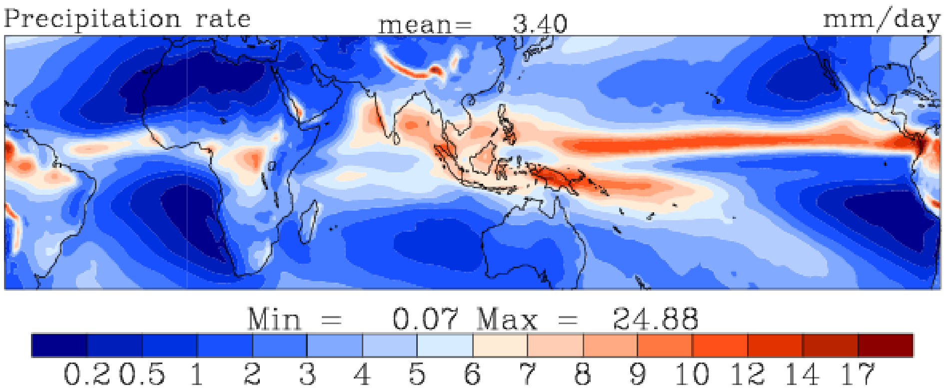
Strengthens further under mesh refinement (CAM4)
Slight improvement in CAM5

Tropical Precipitation Rate

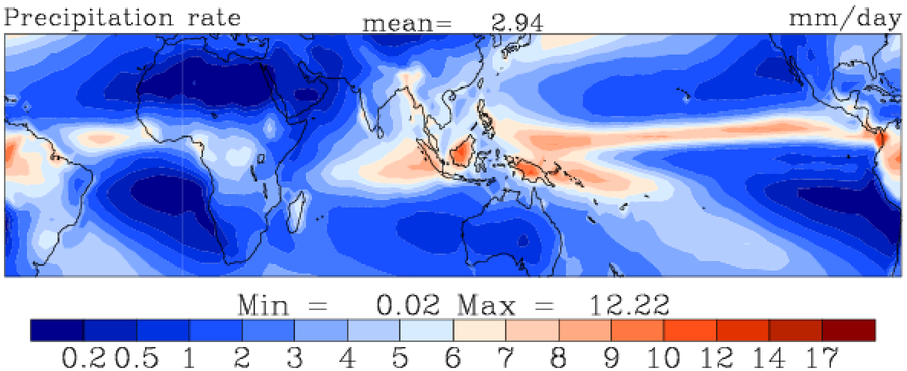
CAM4-SE 1°



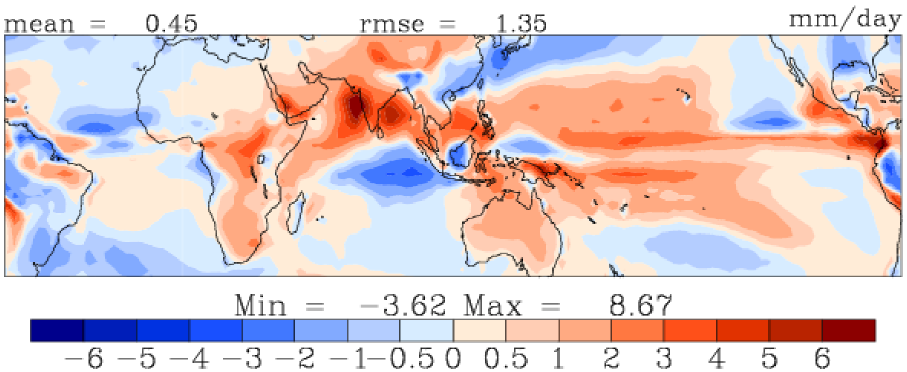
CAM4-FV 1°



GPCP



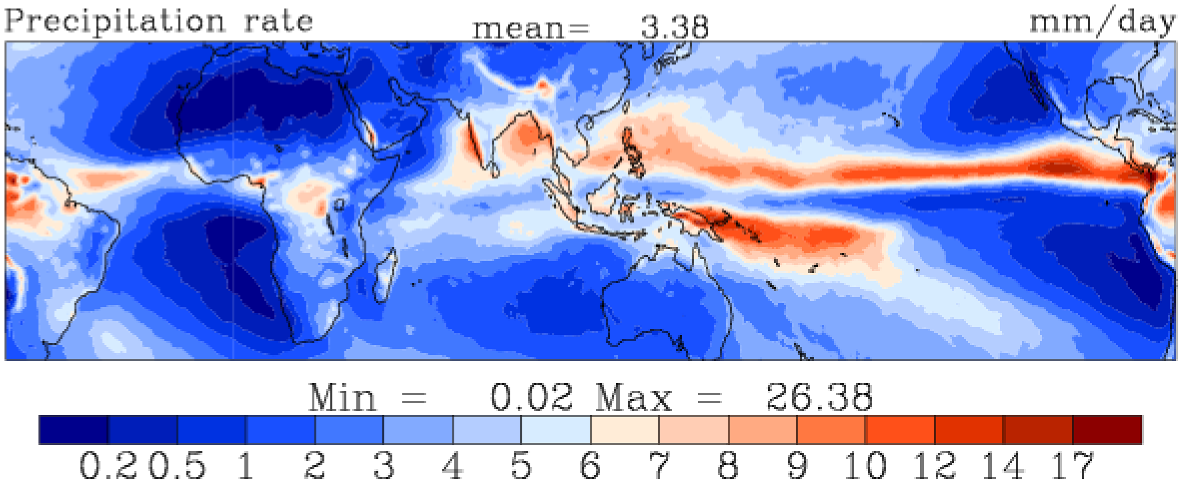
famip_ne30f09e - GPCP



Large biases in both SE and FV

Tropical Precipitation Rate

CAM4-SE 0.25°



CAM5-SE 1°