Initial results and performance of the GFDL Cubed-Sphere Model

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Outline

- Key Features
  - Algorithm Improvements
- Implementation Issues
- Initial Results
  - Hydrostatic (APE, AMIP)
  - Computational performance and scaling
  - Non-hydrostatic
- Future Plans

Key Features

One Model …… Two Configurations

1. Hydrostatic version developed from the well-known FV dynamical core
   - Several improvements/modifications for the cubed-sphere
   - This version is currently working well
2. Non-hydrostatic version
   - Simple switch between hydrostatic and non-hydrostatic versions

     hydrostatic = .false.
   - Easy transition from hydrostatic to non-hydrostatic
   - Non-hydrostatic code is completely independent from the hydrostatic code.
   - 30-50% more expensive than the hydrostatic version at the 4-5 km resolution

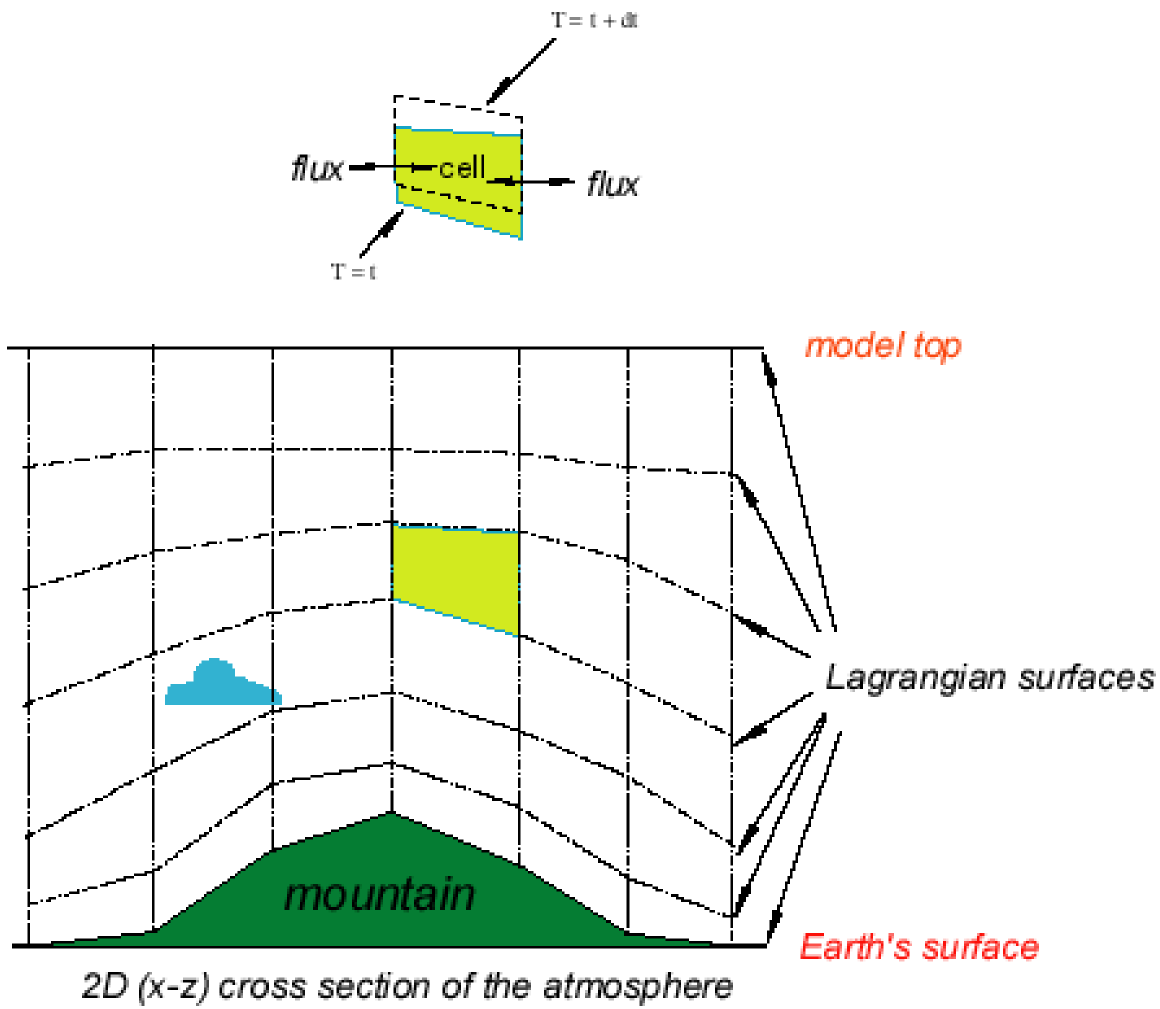
Review of the FV dynamical core

- Conservative, monotonic, flux-form semi-Lagrangian transport for all prognostic variables (*Lin and Rood 1996, MWR*).
- Consistent transport of air mass and absolute vorticity, resulting in a superior transport of the potential vorticity (*Lin and Rood 1997, QJRMS*).
- Finite-volume integration of the pressure gradient forces to more accurately handle steep terrains (*Lin 1997, QJRMS*).
- "V*ertically Lagrangian*" control-volume discretization with mass, momentum, and total energy conserving re-mapping algorithm (*Lin 2004, MWR*).

Algorithm Improvements

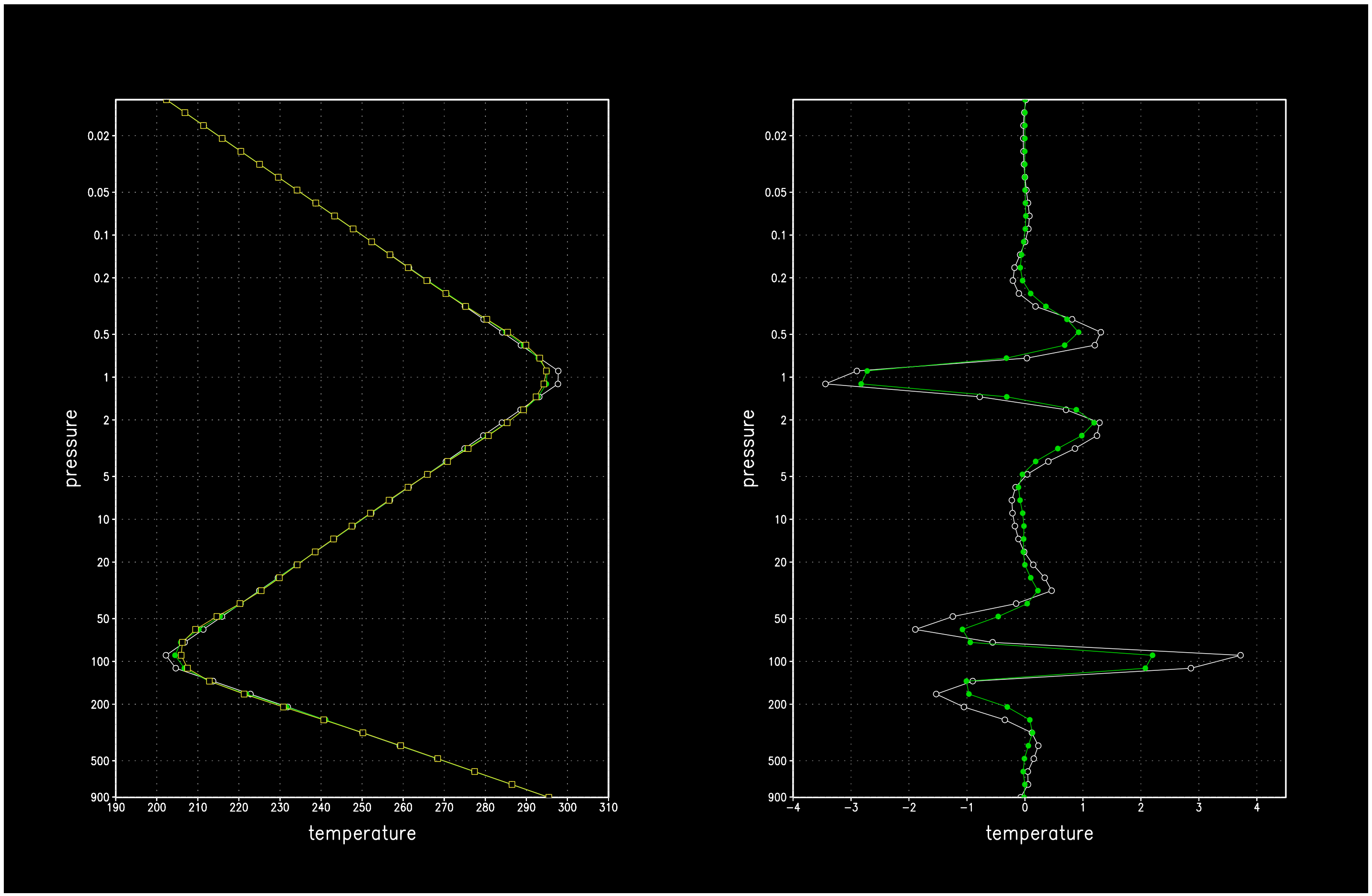
- **Generalization to non-orthogonal curvilinear coordinate**
- **Horizontal transport scheme**
  - fully monotonic for all transported variables (using the same inner and outer 1D operator enhanced stability but slightly more expensive)
  - edges between the 6 faces of the cube are correctly treated as discontinuity
- **4th order interpolation of the winds from D to C grid**
- **The vertical remapping**
  - one-sided extrapolation at the bottom surface and at the model top using cubic polynomials that is coupled with the interior PPM sub-grid reconstruction scheme -- less numerical damping.
  - Geopotential conserving remapping by remapping virtual temperature using log(p) – remapping is exact if the virtual temperature profile can be locally represented by piecewise parabolic polynomials.
- **Communication**
  - pure message passing; communication moved to the outer levels of the code; code is much cleaner and simpler; many OPENMP directives remain but are inactive
- **Lagrangian Riemann Solver for vertically propagating soundwaves**
  - Lin 2007, QJRMS, *in revision*

Vertically Lagrangian Control-Volume Discretization



Improved Remapping

Temperature profiles *Errors*



55 levels
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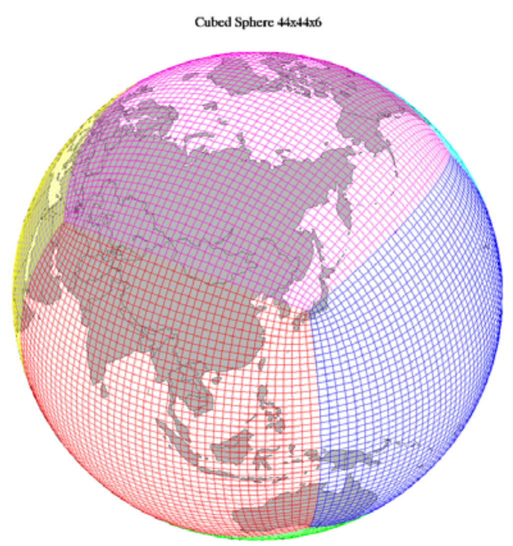
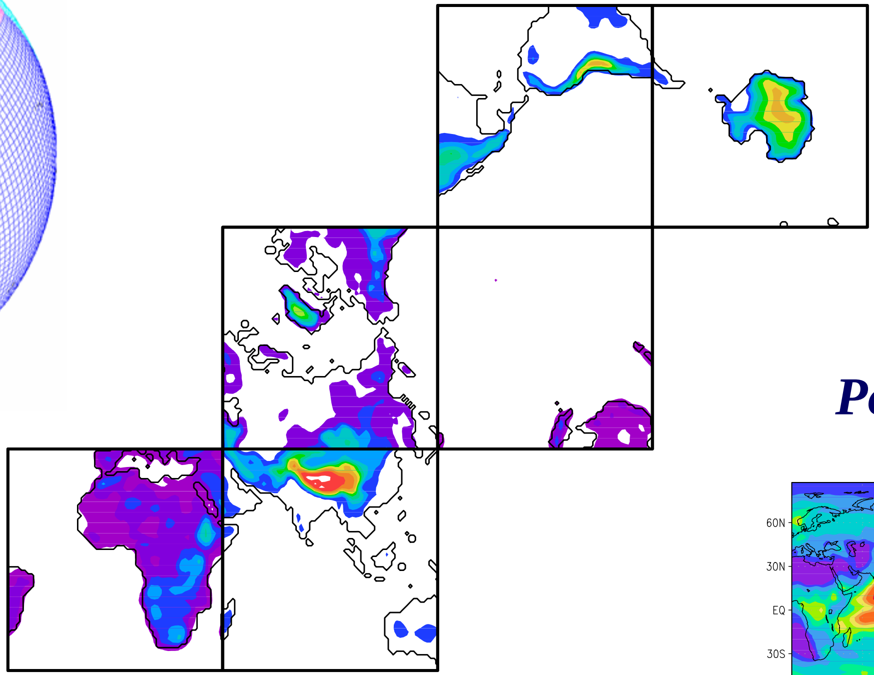
remapped 1000 x

Three ways to look at the cubed-sphere

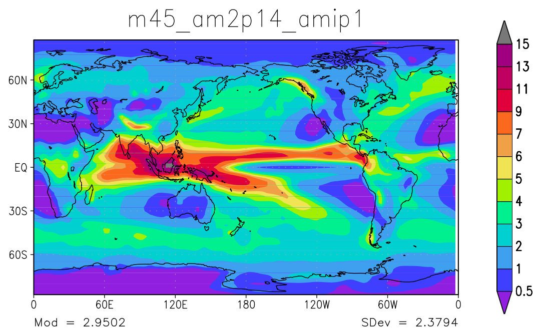
Physical Domain



Computational domain



Post processing



Implementation Issues

- **Cubed-sphere grid choice**
  - Gnomonic grid; analytic solution
  - Spring-dynamics with torsion spring; less distortion at edges and corners
- **Land Model Grid**
  - Cubed-Sphere vs. Latitude-Longitude grid?
  - River routing
- **Coupling software/exchange grid** *(3 step approach)*
  1. By-pass coupler for AMIP runs (all models use the cubed-sphere grid)
  2. CS atmos; LL land; tri-polar ocean and ice models
  3. CS atmos and land; tri-polar ocean and ice models (final configuration)
- **Input data sets**
  - Online lat-lon to cubed-sphere conservative interpolation
- **Diagnostics and post-processing (output data)**
  - Cubed-sphere to lat-lon interpolation

Cubed-sphere grid choices

Gnomonic grid choices compared with lat-lon and Yin-Yang grids.

Grid scheme	Aspect ratio: $\Delta_{MAX} / \Delta_{MIN}$	
	Global grid	Local grid box
Lat-Lon	N	N
Equal distance (Sadourny 1972)	~2	~1.4
Equal angle (Ronchi et al. 1996)	~1.4	~1.4
True equal-distance Gnomonic	~1.4	~1.06
Yin-Yang	~1.4	~1.4

FMS Coupler Overview

Used for data exchange between models. Key features include:

- **Conservation:** Required for long runs.
- **Resolution:** No constraints on component model time steps and spatial grid. Supports both explicit and implicit time stepping.
- **Exchange grid:** Union of component model grids, where detailed flux computations are performed (Monin-Obukhov, tridiagonal solver for implicit diffusion, ...)
- **Fully parallel:** Calls are entirely processor-local: exchange software will perform all inter-processor communication.
- **Single executable:** Serial and concurrent execution in a single executable.
- **Highly efficient**: Currently able to couple atmosphere/ocean explicitly at each ocean time step; atmosphere/land/ice implicitly at each atmospheric time step.

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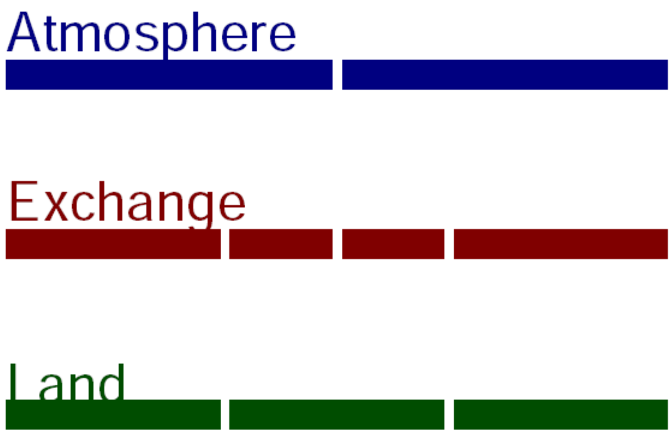
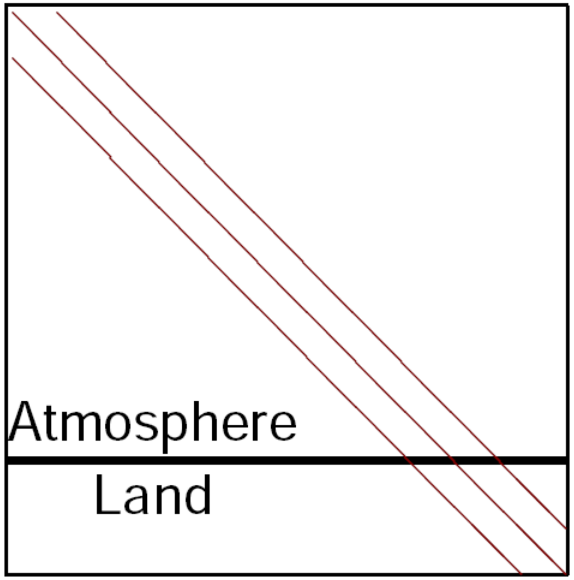
Implicit coupling and the exchange grid

Union of component model grids,
where detailed flux computations are performed.





FMS Coupler: Cubed-Sphere

The fundamentals of the exchange grid do not change as we move to the cubed sphere grid. However, there are some software issues that we are dealing with.

- **New grid specification to accommodate multi-tile grids (mosaics)**
- **Exchange grid generation needs to handle multiple cubed-sphere grids (Atmosphere and Land)**
  - Software originally assumed one of the grids was lat-lon
- **Second-order conservative interpolation**
- **Exchange grid size will be larger**
  - Load balancing; communication costs
  - Code needs to be very efficient
- **Earth System Model (ESM) will exchange even more tracers**
  - Need for efficient code even greater

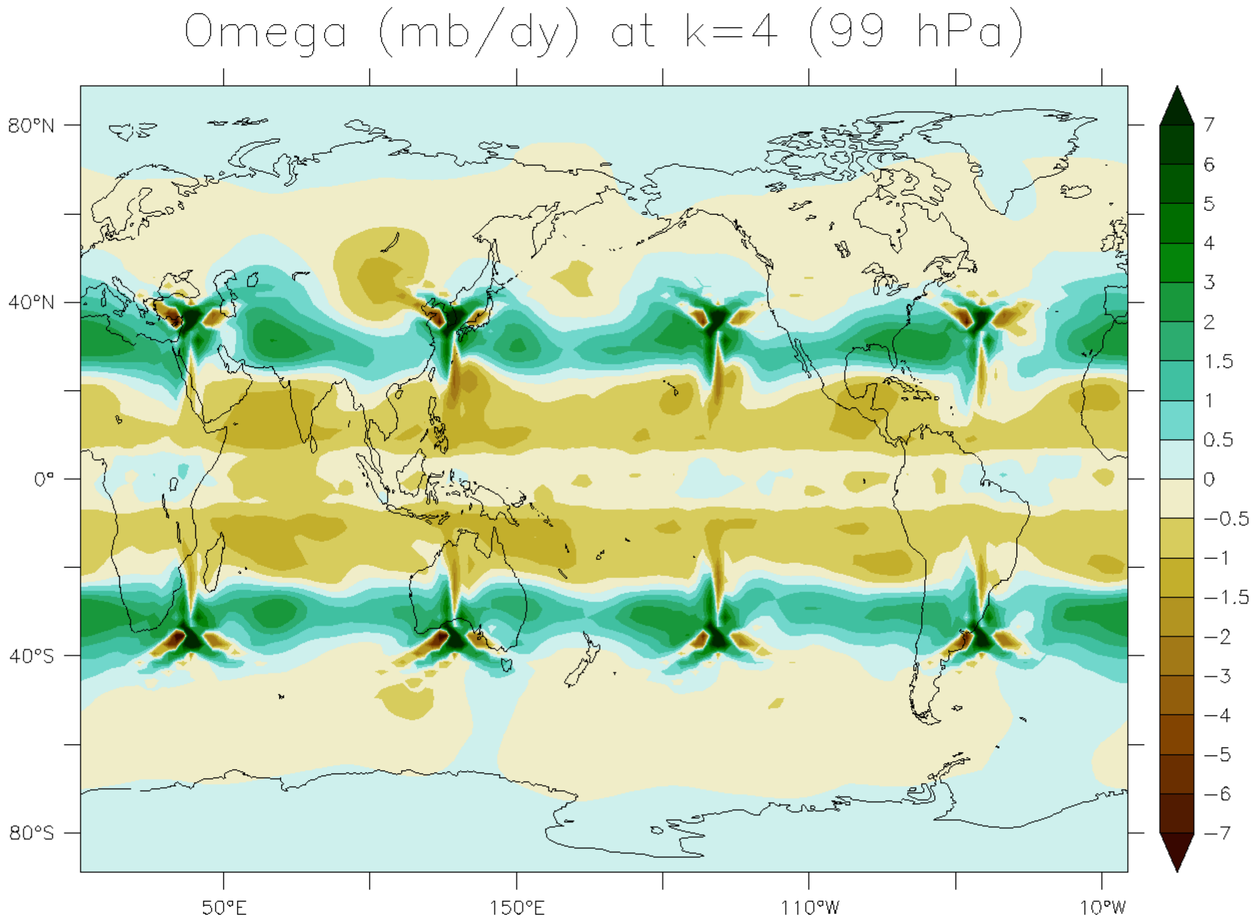
Initial Tests (Hydrostatic Model)

- **Aqua-planet runs**
  - Neale and Hoskins (2001)
  - Specified zonally symmetric SST (Control case #1)
  - Diurnal radiation with NO annual cycle
  - Radiative gases held constant or turned off
- **AM2 physics**
- **No coupling software**
- **Good for identifying problems at the corners**
- **Examine 3 year annual averages**

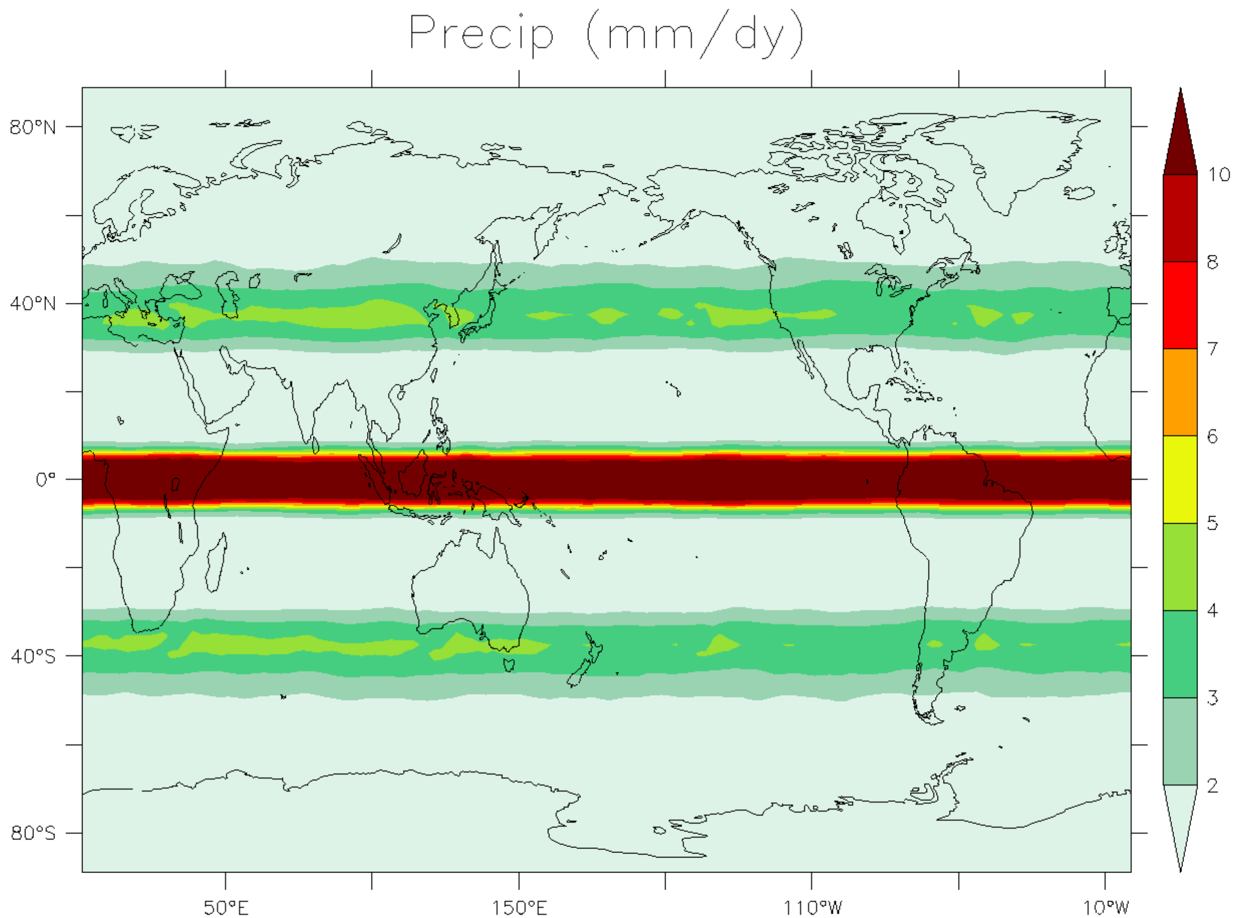
AM2 Physics *(J. of Climate, Dec. 2004)*

- **Radiation:** Diurnal cycle with full radiation calculation every 3 h; effects of H_2O, CO_2, O_3, O_2, N_2O, CH_4, and four halocarbons included. **Longwave:** Simplified exchange approximation (Schwarzkopf and Ramaswamy 1999); Clough et al. (1992) CKD 2.1 H_2O continuum parameterization. **Shortwave:** Exponential sum fit with 18 bands (Freidenreich and Ramaswamy 1999); liquid cloud radiative properties from Slingo (1989); ice cloud radiative properties from Fu and Liou (1993).
- **Aerosols:** Prescribed monthly three-dimensional climatology from chemical transport models; species represented include sulfate, hydrophilic, and hydrophobic carbon, dust, and sea salt.
- **Clouds:** Three prognostic tracers; cloud liquid, cloud ice, and cloud fraction; cloud microphysics from Rotstayn (1997) and cloud macrophysics from Tiedtke (1993).
- **Convection Relaxed Arakawa–Schubert:** From Moorthi and Suarez (1992); Detrainment of cloud liquid, ice, and fraction from convective updrafts into stratiform clouds; a lower bound imposed on lateral entrainment rates for deep convective updrafts (Tokioka et al. 1988); convective momentum transport represented by vertical diffusion proportional to the cumulus mass flux.
- **Vertical diffusion:** Surface and stratocumulus convective layers represented by a K-profile scheme with prescribed entrainment rates (Lock et al. 2000); surface fluxes from Monin–Obukhov similarity theory; gustiness enhancement to wind speed used in surface flux calculations (Beljaars 1995); enhanced near-surface mixing in stable conditions; orographic roughness effects included.
- **Gravity wave drag:** Orographic drag from Stern and Pierrehumbert (1988)
- **Land model:** Isothermal surface (soil–snow–vegetation); three water stores: snow, root zone, and ground water; 18 soil temperature levels to 6-m total depth; stomatal control of evapotranspiration; latent heat storage in soil; surface parameters dependent on eight soil and eight vegetation types

C44 Aqua-planet experiment



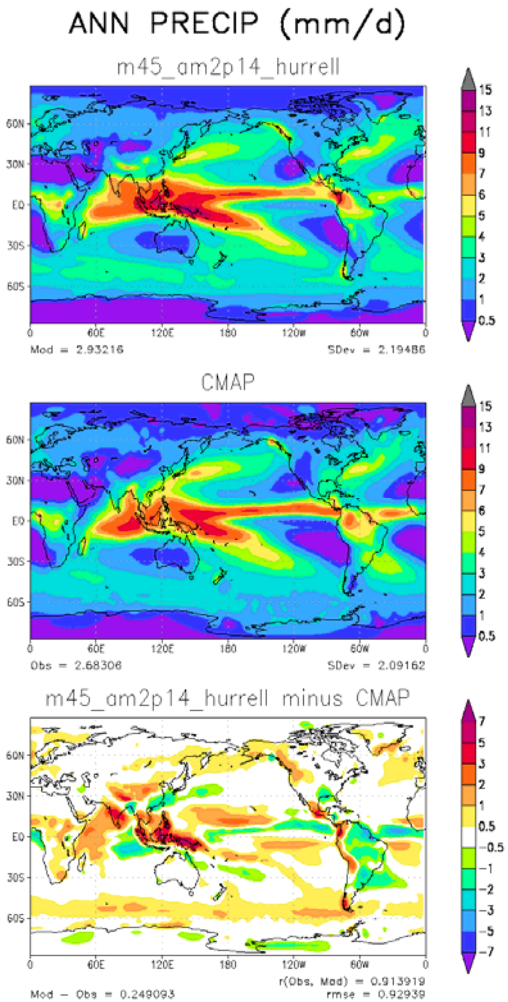
C44 Aqua-planet experiment

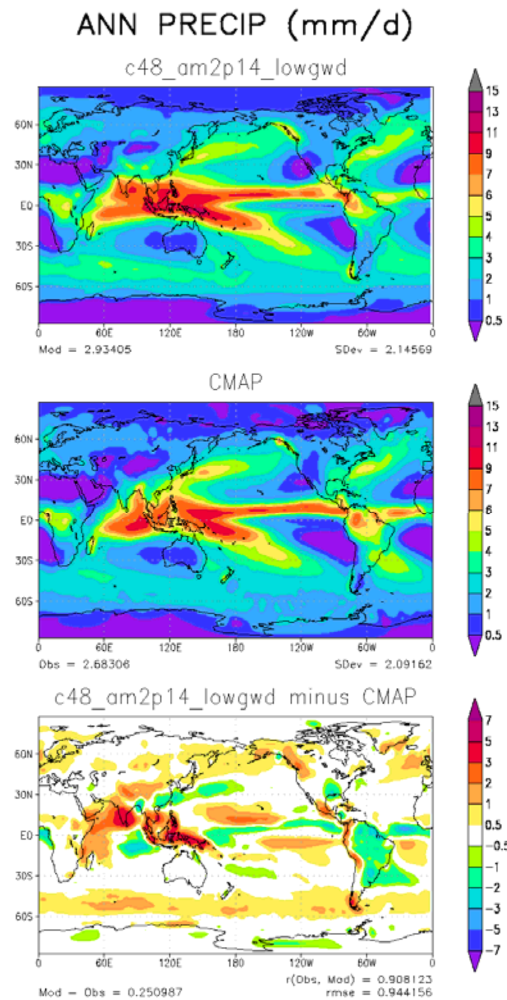


Initial Tests (Hydrostatic Model)

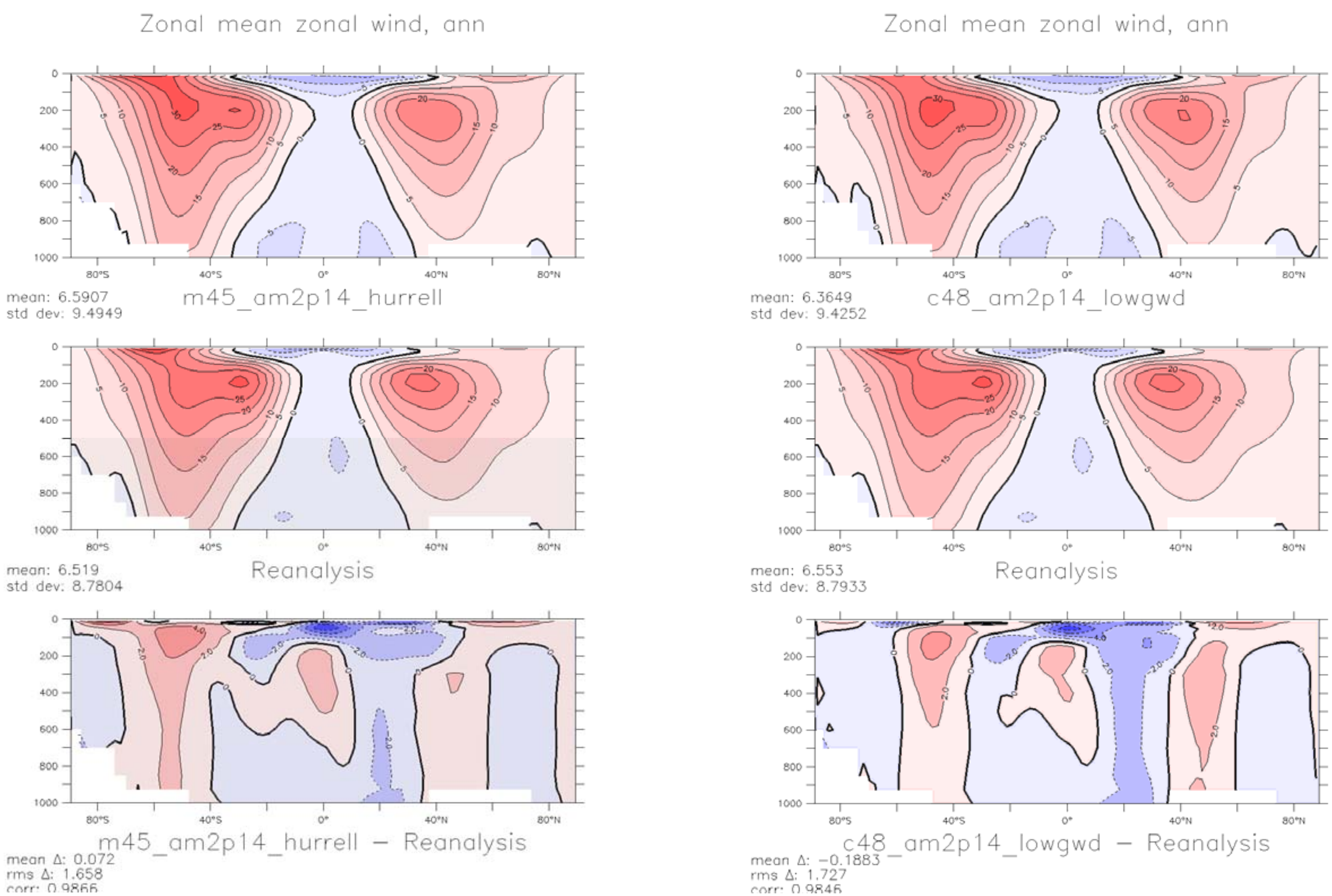
- AMIP runs
  - Same as AM2p14 except …
    All component models are on the cubed-sphere
    No exchange grid (coupling software)
- C48 L24
  - Each face has 48x48 points; approx. 2 degree resolution
    Similar horizontal resolution to AM2p14 (M45)
  - Same vertical resolution as AM2
- 21 year integration: 1980-2000 (Hurrell SST/ICE)
- Several integrations completed at C64 and C90

AMIP Results

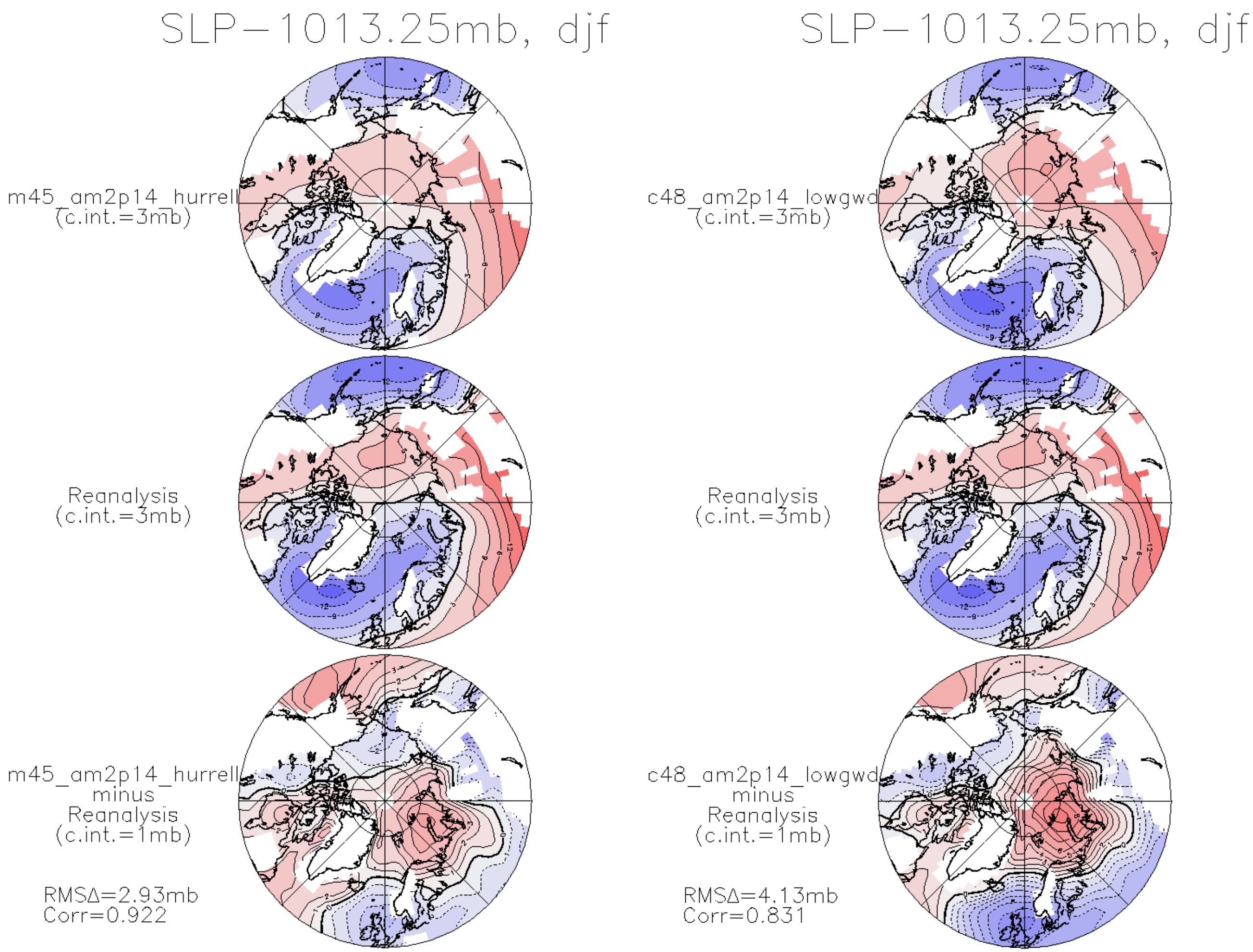




AMIP Results



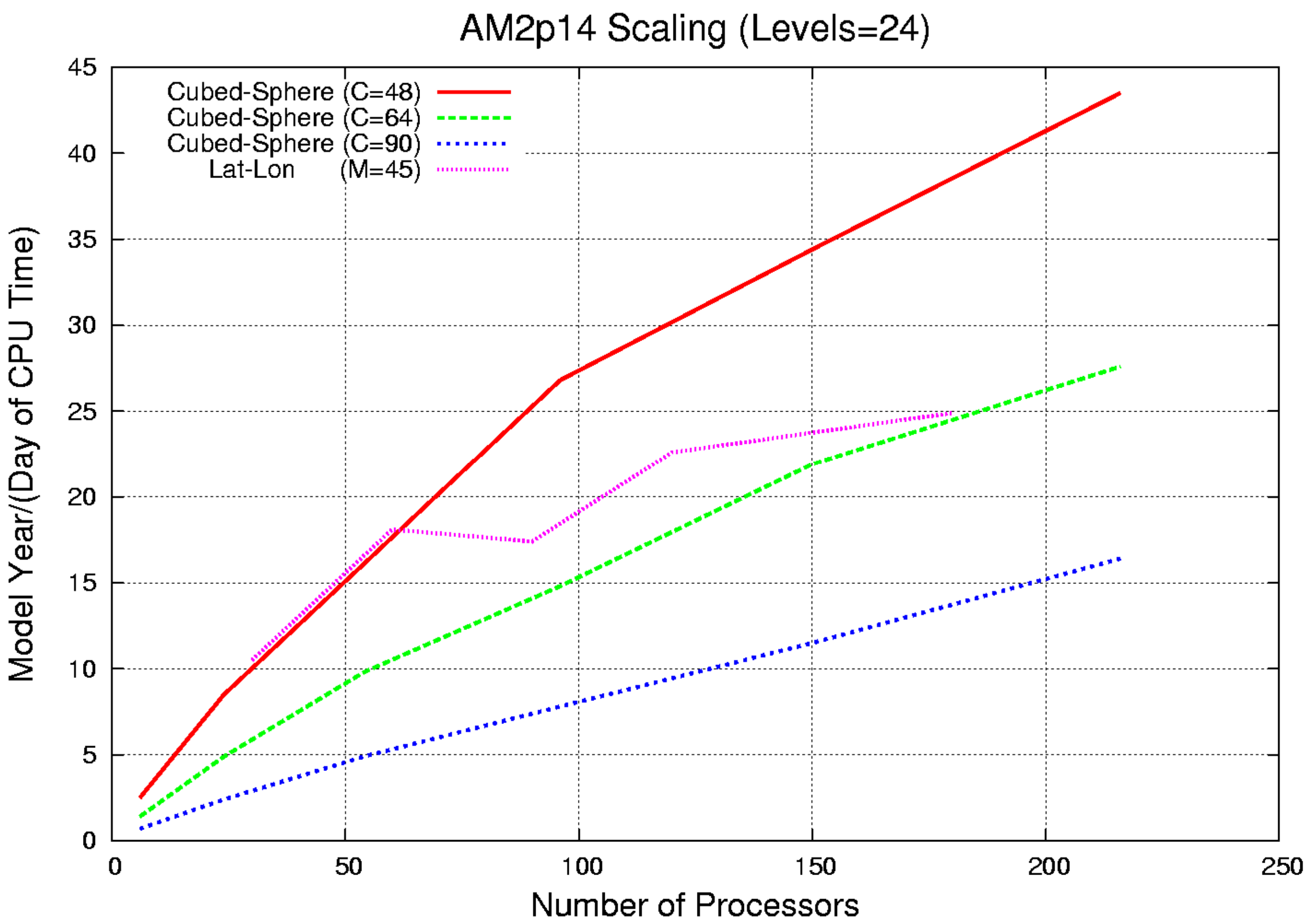
AMIP Results



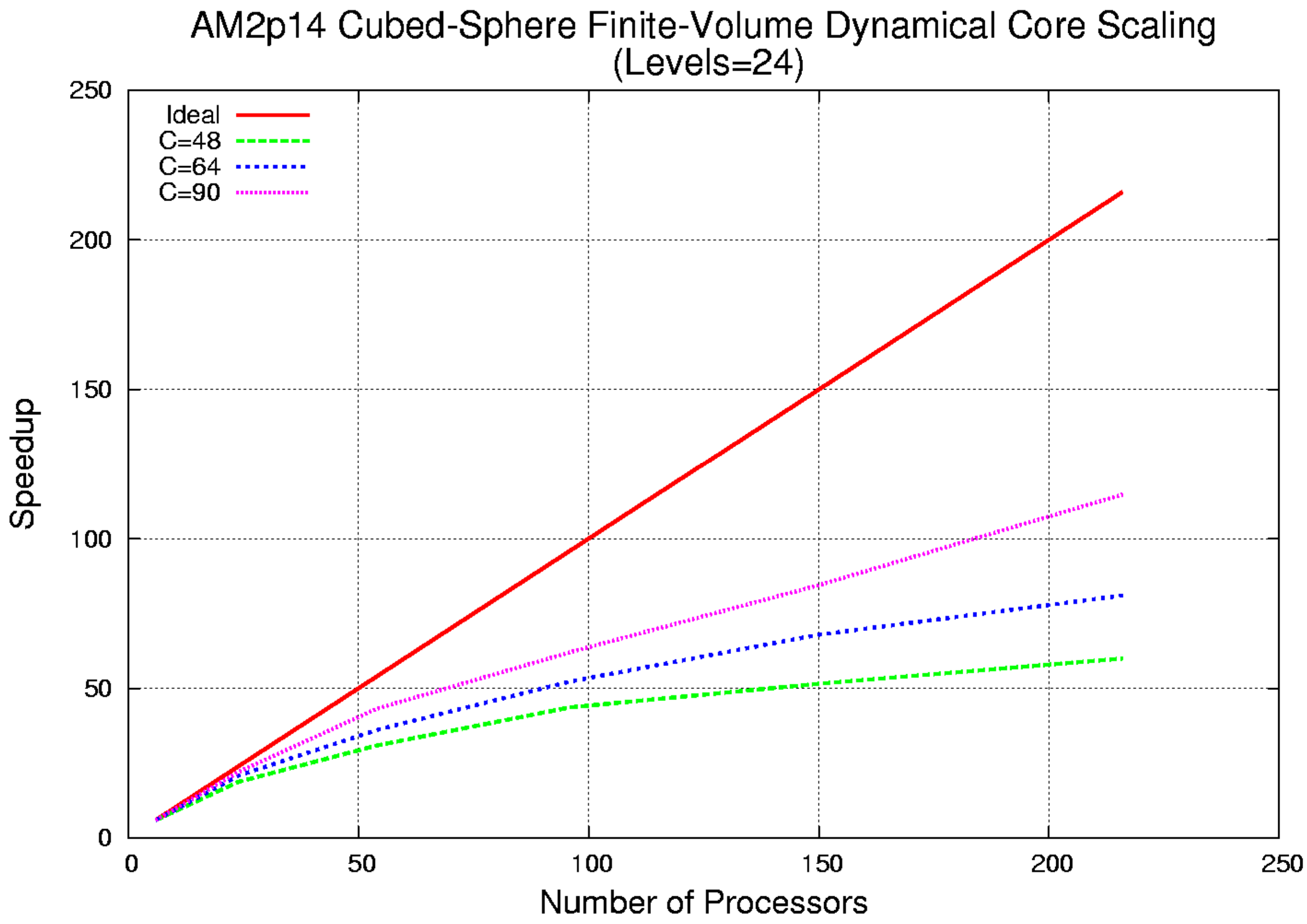
Comments on the cubed-sphere

- Arctic climate
  Will it improve with higher horizontal resolution?
  How much improvement can be gained with tuning GWD?
- Coupler/exchange grid overhead
  More exchange grid cells and more communication.
  Earth system model exchanges many more tracers.
  Diagnostics of quantities on the exchange grid may also be costly.
  Possible solution: Perform many *puts/gets* with the exchange grid at a time.
- Post-processing: Cube to Lat-Lon
  Integration with the GFDL post-processing software. Interpolation to standard pressure levels should be done on the cubed-sphere grid.
- Interpolation of input data sets
  High-resolution lat-lon to cubed-sphere is very costly.
  Move some online interpolation to offline?
- Scaling
  Will the benefits of scaling out weight the issues above?

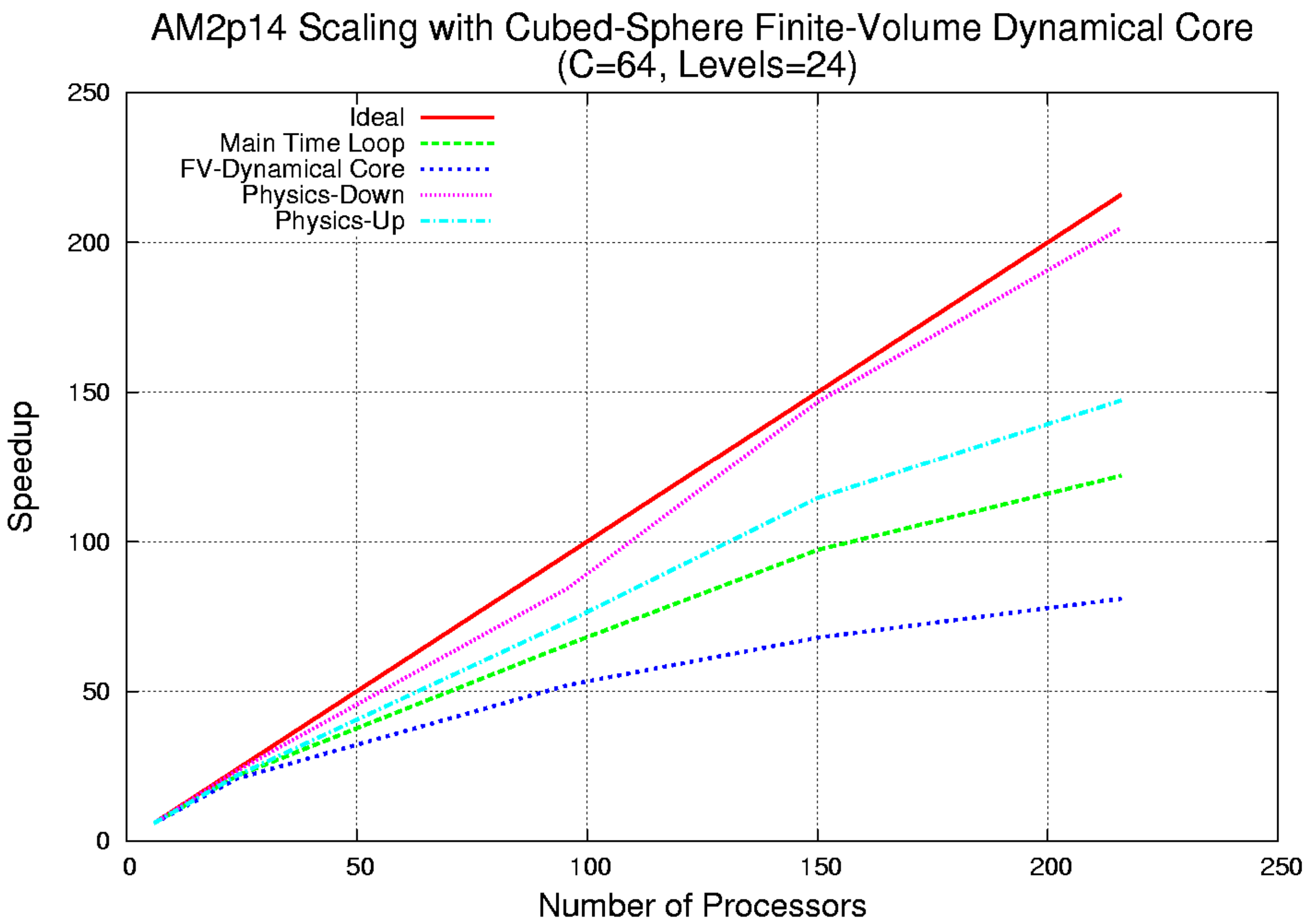
Scaling of AMIP runs



Scaling of the dynamical core



Scaling of C64 AMIP run



Vertically Lagrangian Non-Hydrostatic FV Core

$$\frac{\partial}{\partial t}\delta p^* + \nabla_h \cdot \left[\vec{V}\delta p^*\right] = 0$$

$$\frac{\partial}{\partial t}(\Theta\delta p^*) + \nabla_h \cdot \left[\vec{V}\Theta\delta p^*\right] = 0$$

$$\frac{\partial}{\partial t}u - \Omega\tilde{v}\sin\alpha + \frac{\partial}{\partial x}\left(\frac{\tilde{u}u+\tilde{v}v}{2}\right) = \frac{\delta\Phi}{\delta p^*}\left[\frac{\partial p}{\partial x}\right]_z = \frac{\delta\Phi}{\delta p^*}\left[\frac{\partial p'}{\partial x}\right]_z + \frac{\delta\Phi}{\delta\pi^*}\left[\frac{\partial\pi^*}{\partial x}\right]_z$$

$$\frac{\partial}{\partial t}v + \Omega\tilde{u}\sin\alpha + \frac{\partial}{\partial y}\left(\frac{\tilde{u}u+\tilde{v}v}{2}\right) = \frac{\delta\Phi}{\delta p^*}\left[\frac{\partial p}{\partial y}\right]_z = \frac{\delta\Phi}{\delta p^*}\left[\frac{\partial p'}{\partial y}\right]_z + \frac{\delta\Phi}{\delta\pi^*}\left[\frac{\partial\pi^*}{\partial y}\right]_z$$

optional

$$\frac{\partial}{\partial t}(w\delta p^*) + \nabla_h \cdot \left[\vec{V}w\delta p^*\right] = g\delta p'$$

$$\delta m = \delta p^*/g = -\rho\delta Z$$

$$p = p^* + p'$$

$$\frac{\partial}{\partial t}\delta z + \delta\left[\vec{V}\bullet\nabla_h z\right] = \delta W$$

hydrostatic →

$$\delta z = \frac{1}{g}C_p\Theta\delta\pi^*$$

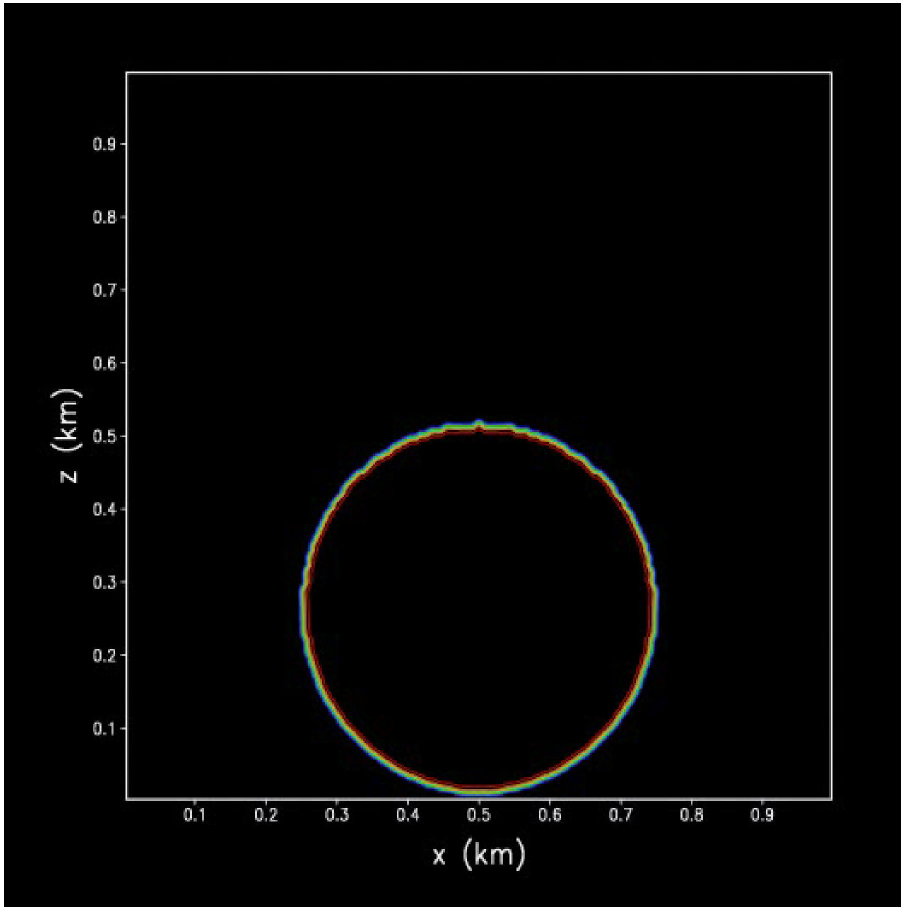
[A Riemann solver is used for the non-hydrostatic adjustment]

Lagrangian Riemann solver *versus* semi-implicit finite differencing

- Advantages
  - Acoustic waves are treated more accurately.
  - No staggering of prognostic variables is necessary. The exact Riemann solver provides, in effect, an analytic way of staggering for pressure gradient computation.
  - Computationally more efficient at cloud-resolving scales
- Disadvantages
  - There is a physical limit on the size of the time; sub-cycling becomes necessary if the resolution is near the hydrostatic regime (~10km and beyond). Therefore, it is slower than semi-implicit algorithm for hydrostatic scales.
  - Not applicable for Eulerian coordinate systems.

Non-hydrostatic test case

Warm bubble experiment (Robert 1992): $\Delta x = \Delta z = 5m$, $D=0.1$, $\Delta t = 0.1s$

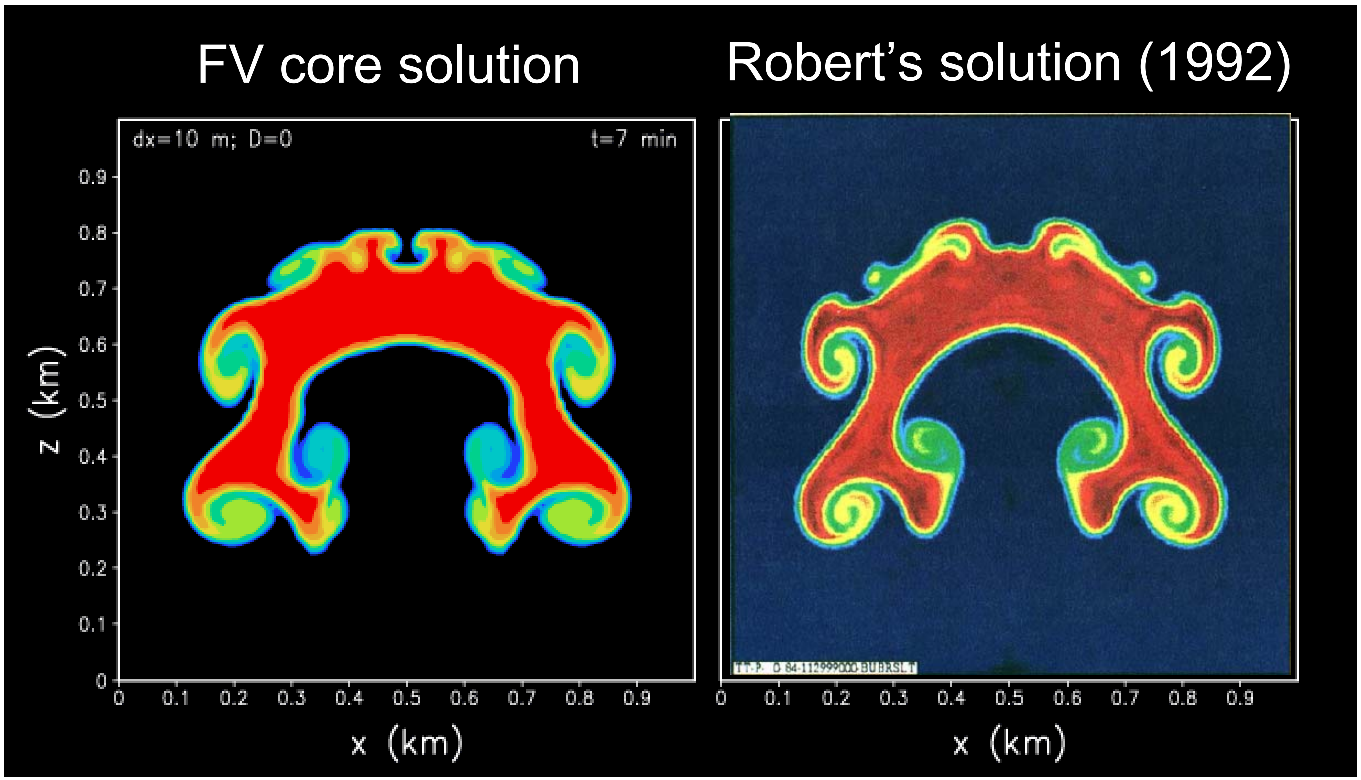


Initial condition:
isentropic with
warm bubble perturbation

Contours:
potential temperature

Non-hydrostatic test case

Warm bubble (Robert 1992)



Global Non-Hydrostatic Core

- Test cases run at C1000 and C2000
  - C2000 is approximately 4-5 km resolution
  - Jablonowski & Williamson (2006) with 4 tracers
- 864 processors used on the GFDL SGI Altix 4700
  - computational domain on a single processor of ~ 167 x 167 x 26 points

Global Non-Hydrostatic Core

Performance at various horizontal resolutions

Model	Grid size (km)	Physics & remapping time step (seconds)	2D Lagrangian dynamics time step (seconds)	Riemann solver time step (seconds)	Throughput (days/day)
C720 26L	*10.9~15.4*	*360*	*15*	*5*	*~64**
C1000 26L	*7.8~11.1*	*240*	*12*	*4*	*~32*
C2000 26L	*3.9~5.5*	*120*	*6*	*3*	*~4.2*

Global Non-Hydrostatic Core

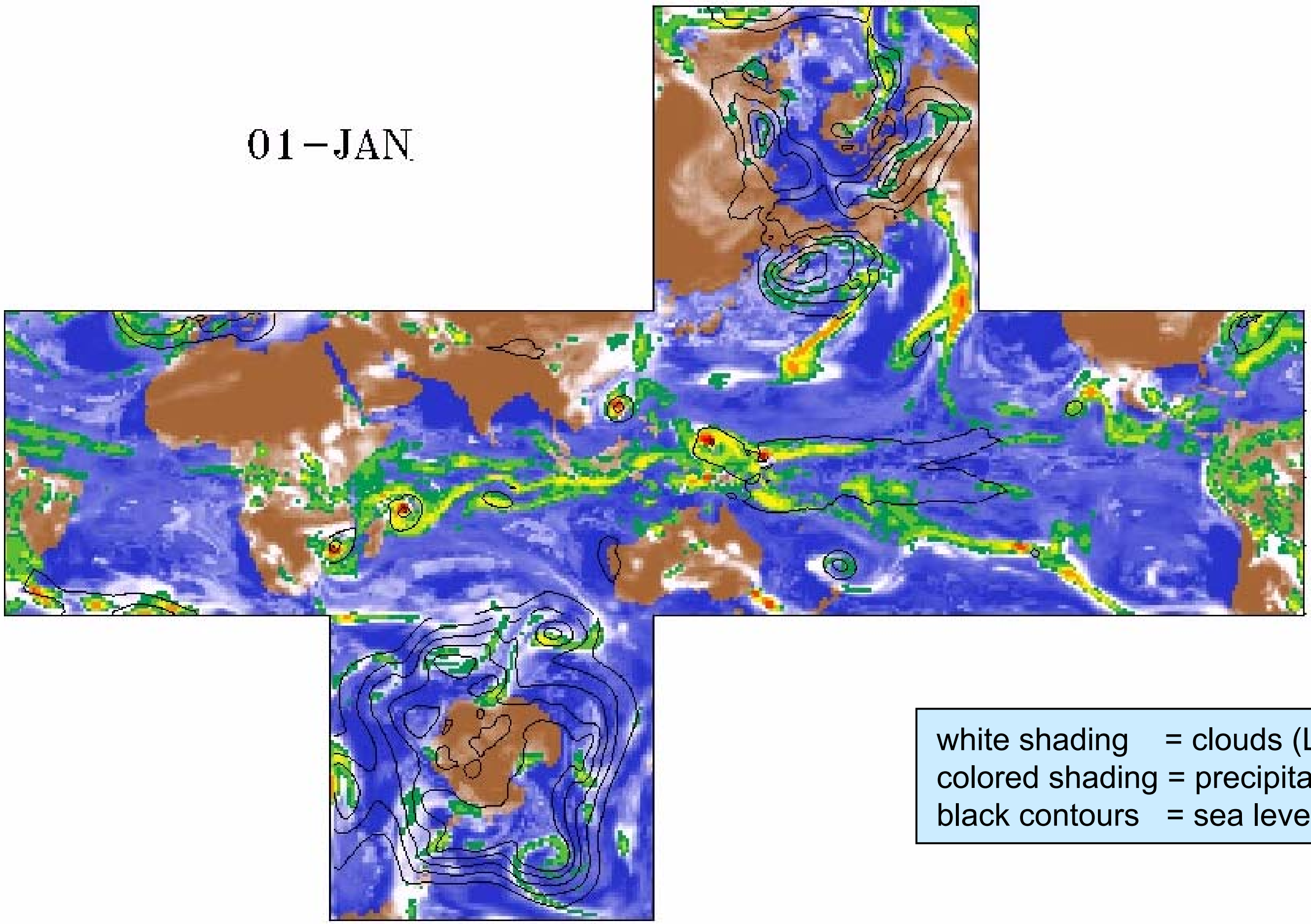
Timing breakdown for C2000 resolution (1 day run)

Total (seconds)	20265.8	100%
Horizontal Advection (20 sub-cycles within the Lagrangian dynamics)	7463.4	36.8
Riemann Solver (3 sub-cycles per small step)	7411.1	36.6
Message Passing	1410.4	7.0
Lagrangian to Eulerian Remapping	1093.74	5.4
Pressure gradients (C+D core)	680.7	3.4
Tracer advection (large-time-step)	544.3	2.2
Others (initialization, diagnostics, etc.)	1662.2	8.4

Future Plans

- Incorporate into AM3 *(our next AM)*
- Doubly-periodic limited-area model
  - Test bed for physics, import cloud micro-physics
- Global high-resolution hydrostatic model
  - C360 (¼°), AMIP mode, less obtrusive convection
- Global cloud-resolving non-hydrostatic model
  - C2000 (4-5 km), short term forecasts, proof of concept run
- Regional grids and nesting

C90 Movie



white shading = clouds (LWP+IWP)
colored shading = precipitation
black contours = sea level pressure