A 3-D Finite-Volume Nonhydrostatic Icosahedral Model (NIM)

Jin Lee

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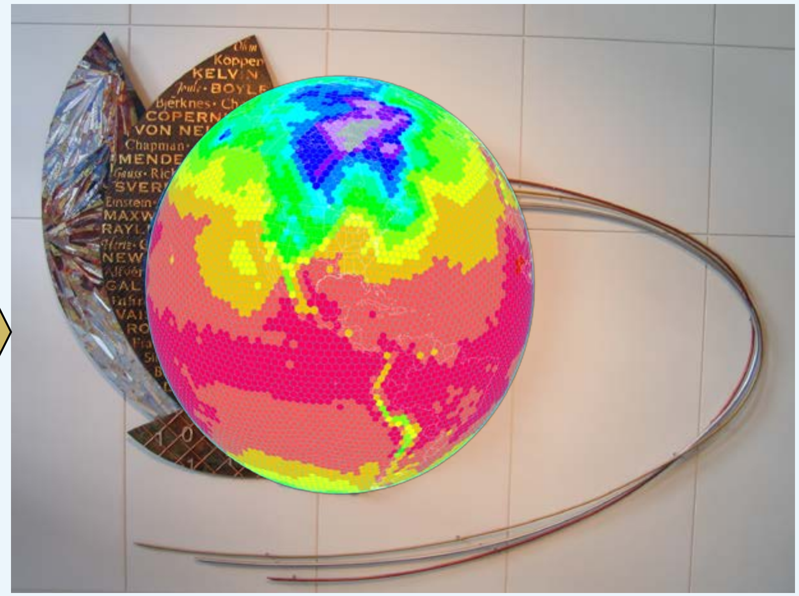
GFDL,NSSL,ARL,AOML,GLERL,PMEL

Aeronomy Lab.
Climate Diagnostic center
Climate Monitoring and Diagnostic Lab
Environmental Technology Lab
Forecast Systems Lab



Chemical Sciences Div
Global Monitoring Div
Physical Sciences Div
Global Systems Div

Modeling goal: to develop a non-hydrostatic icosahedral global model for ***weather*** and ***climate*** predictions

ESRL Finite-Volume Icos-Models (FIM/NIM)

ESMF

Hydrostatic

FIM

Flow-Following Finite-volume Icosahedral Model

- Target resolution **≥ 10 km**
- A hydrostatic model consists of 2-D finite-volume SWM coupled with hybrid σ-θ vertical solver.
- Produce accurate medium-range weather forecasts

Non-Hydrostatic

NIM

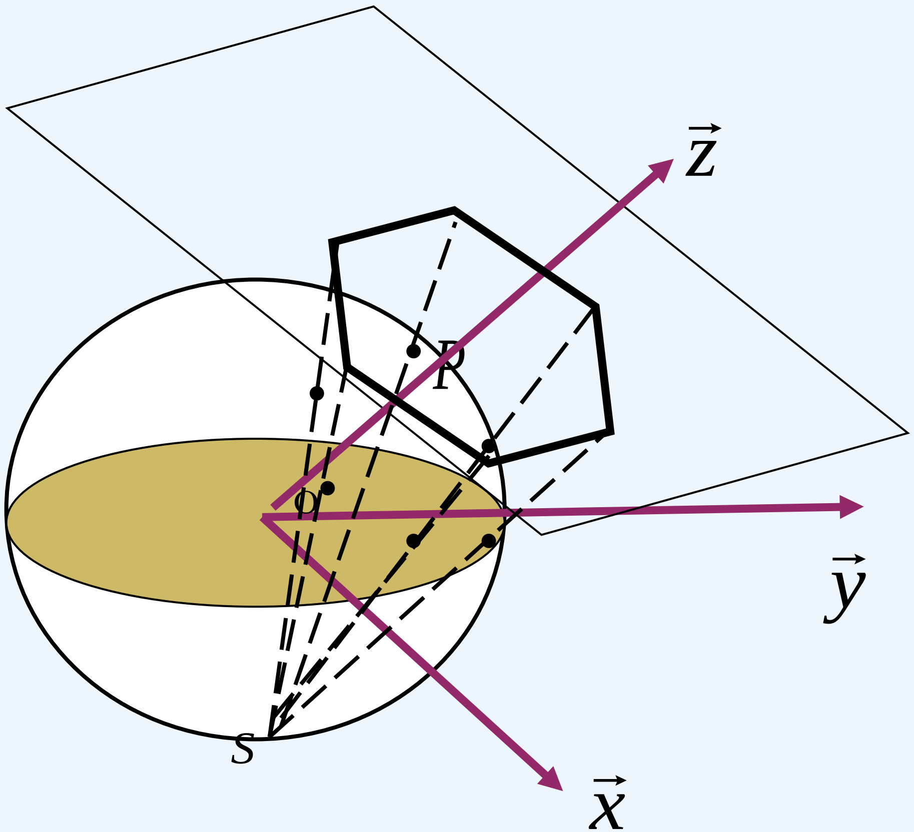
Nonhydrostatic Icosahedral Model

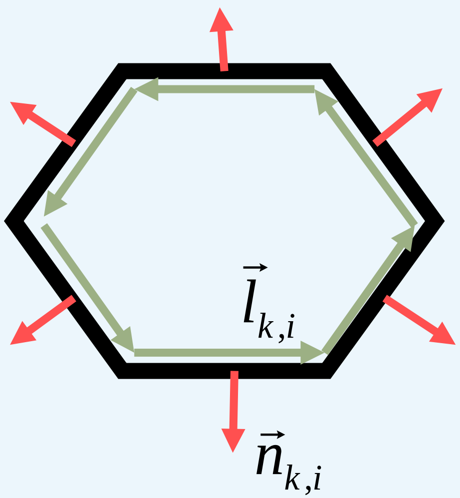
- Target resolution : **O (1 km) and beyond**
- Extension of 2-D finite-volume integration into 3-D integration on control volume for multi-scales simuliations.
- Use the latest GPU technology to speed up high-resolution model calculations.

Novel features of FIM/NIM:

- **Finite-volume Integrations on *Local Coordinate***

Lee and MacDonald (*MWR, 2009*): A Finite-Volume Icosahedral Shallow Water Model on Local Coordinate.





2-D f.-v. operator carried out on straight lines, rather than along the 3-D curved lines on the sphere

Novel features of FIM/NIM:

- **Finite-volume Integrations on *Local Coordinate***
- **Conservative and Monotonic Adams-Bashforth 3rd-order FCT Scheme**

- Lee, Bleck, and MacDonald (2010, JCP): A Multistep Flux-Corrected Transport Scheme.

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- Bleck, Benjamin, Lee and MacDonald (2010, MWR): On the Use of an Arbitrary Lagrangian-Eulerian Vertical Coordinate in Global Atmospheric Modeling.

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- **FIM: Hybrid σ-θ Coordinate w/ GFS Physics**
- **Efficient Indirect Addressing Scheme on Irregular Grid**

- MacDonald, Middlecoff, Henderson, and Lee (2010, IJHPC) : A General Method for Modeling on Irregular Grids.

.

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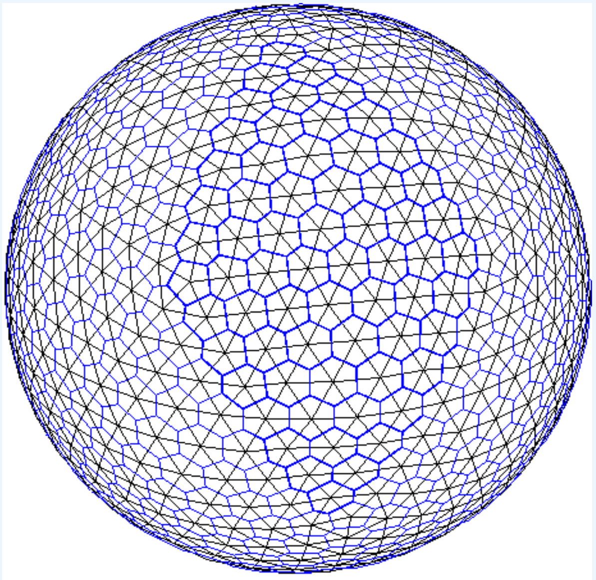
- **Grid Optimization for Efficiency and Accuracy**

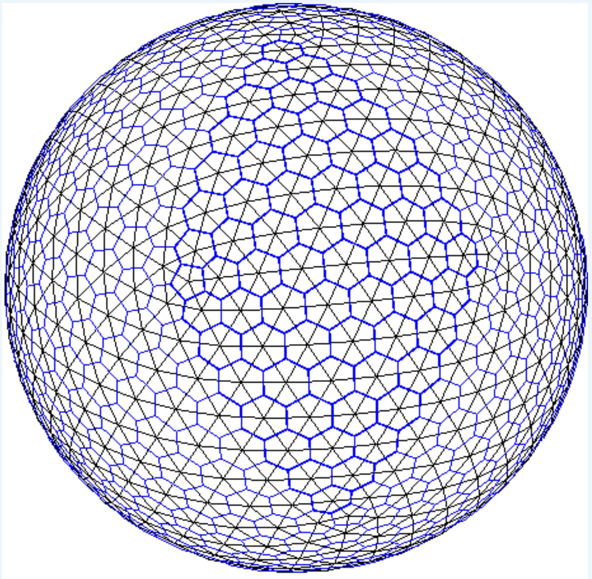
  - Wang and Lee (2011, SIAM): Geometric Properties of Icosahedral-Hexagonal Grid on Sphere.

Comparisons of Icosa-grids

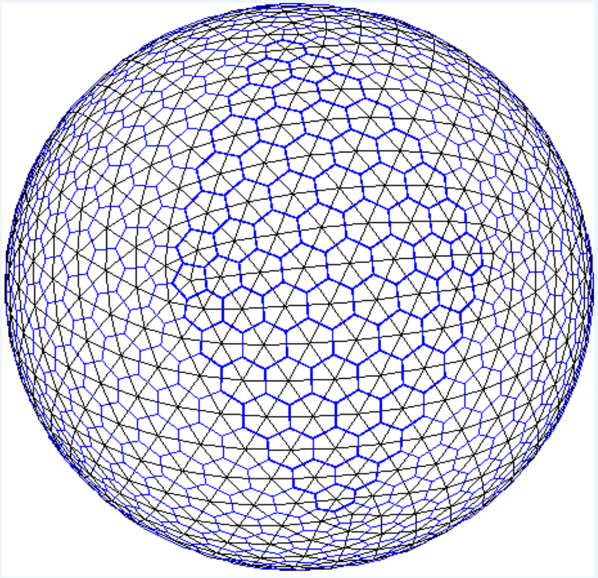
SBiR



SPDN

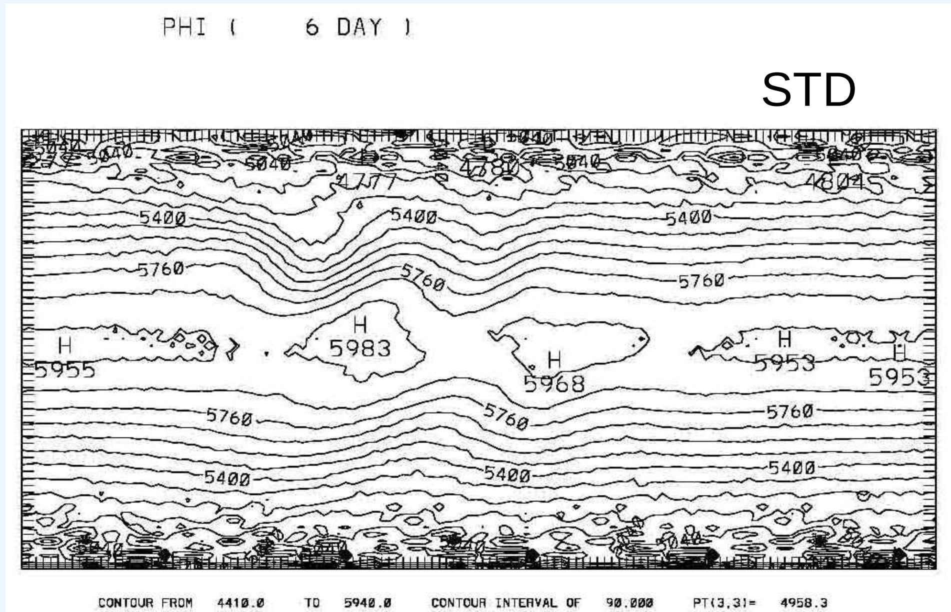


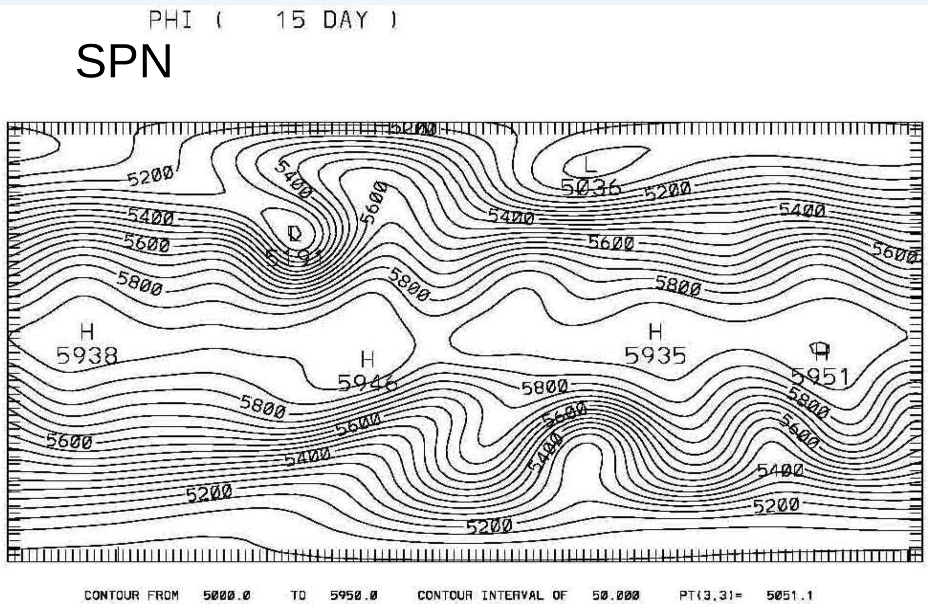
MGCL

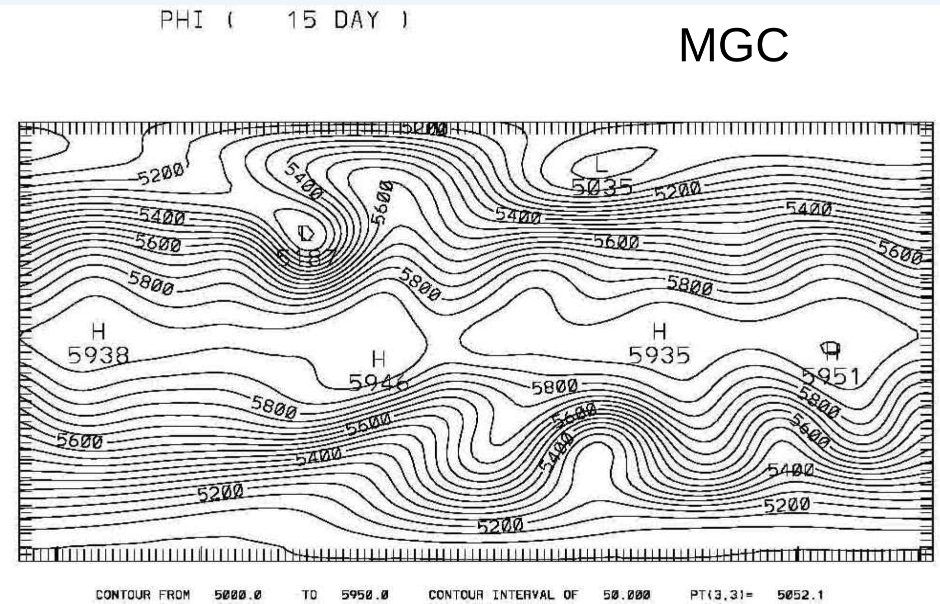


	Uniformity	Regularity
SBiR	**1.195**	**1.476**
MBiR	1.175	1.405
SGCL	1.476	1.194
MGCL	**1.446**	**1.135**

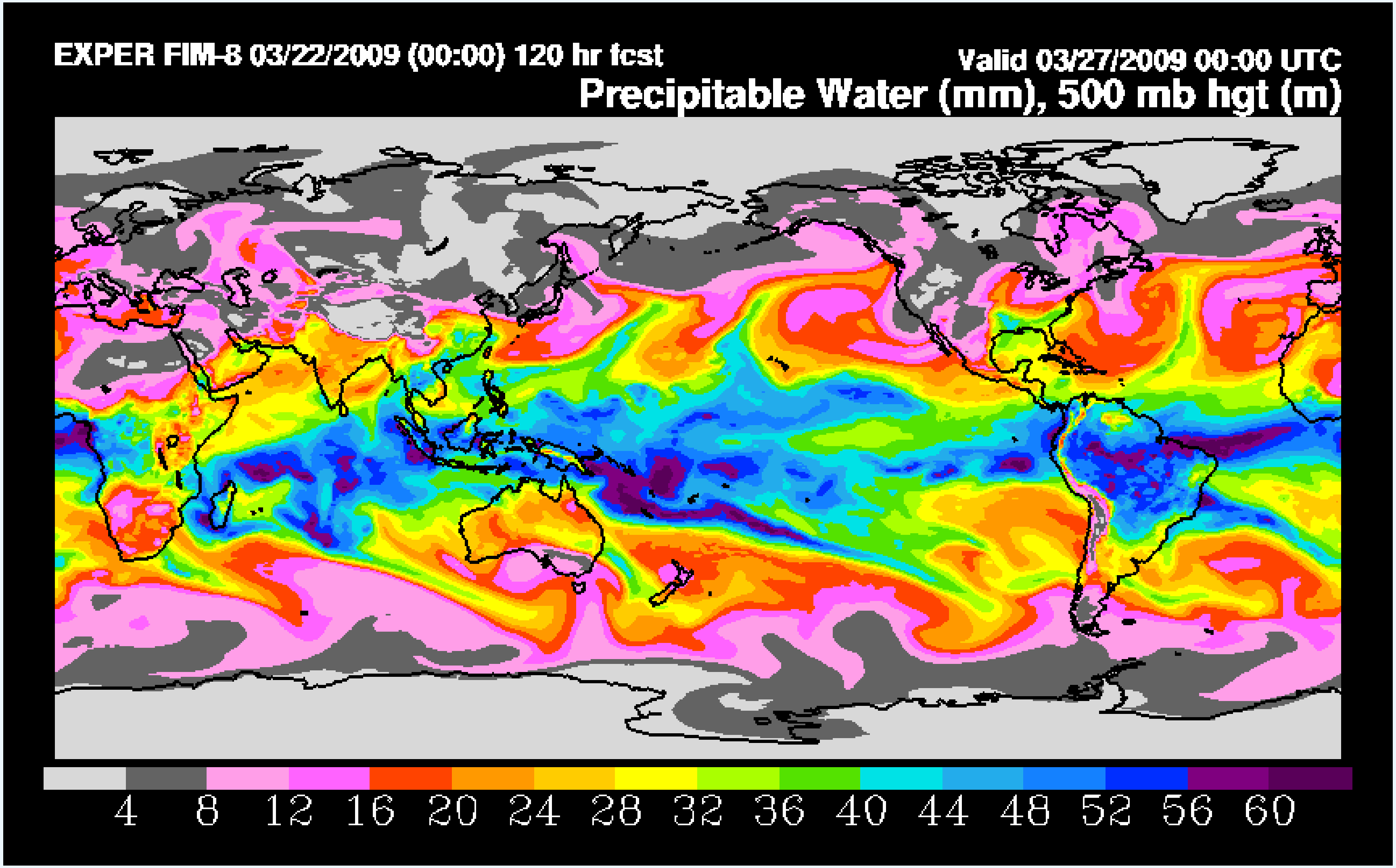
Williamson etal.(1992) Case V: ***Zonal flow over Mountain (no dissipation)***



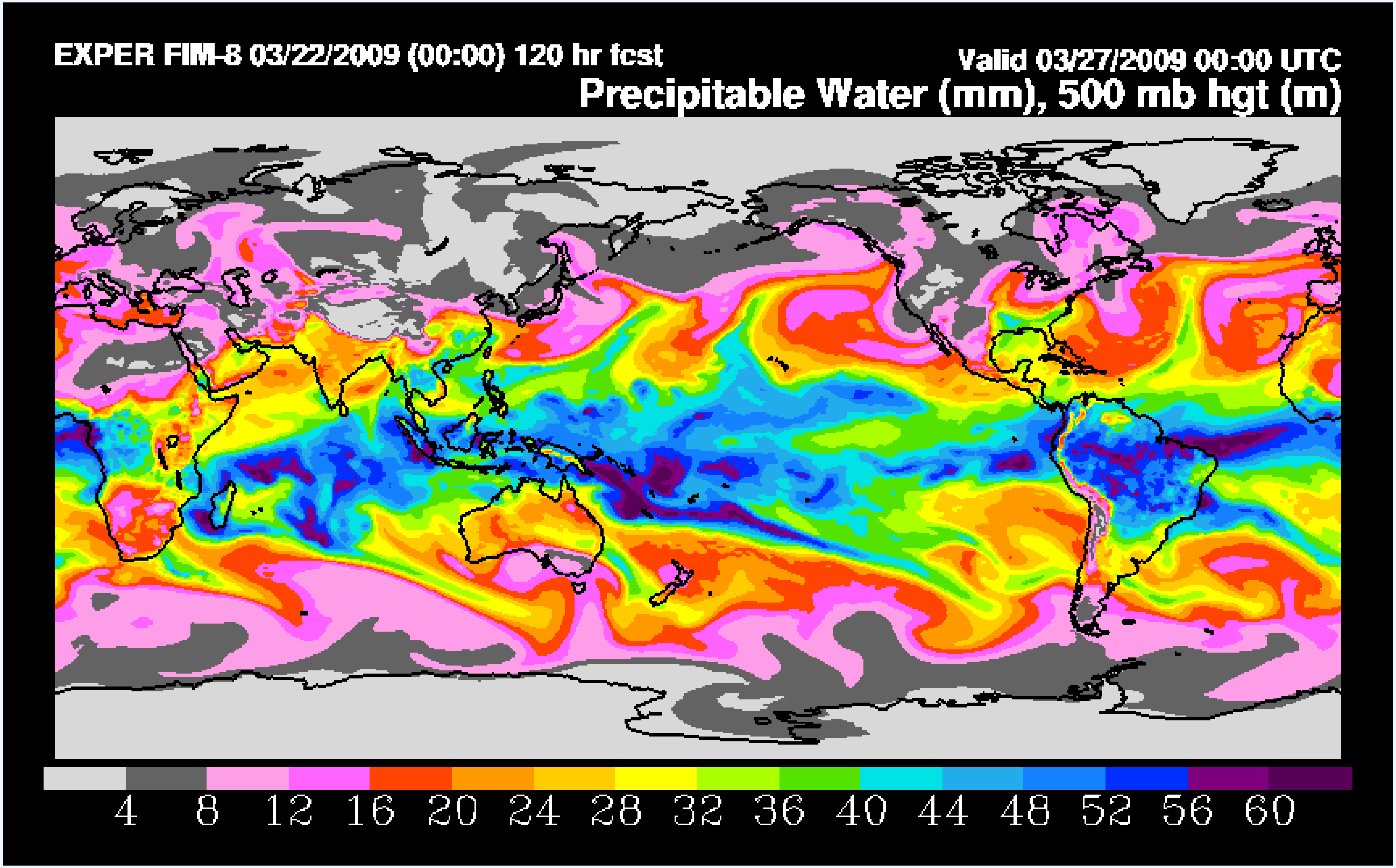




SBiR (G8/dt=45 sec)



MGCL (G8/dt=36 sec, blow up with dt=45)



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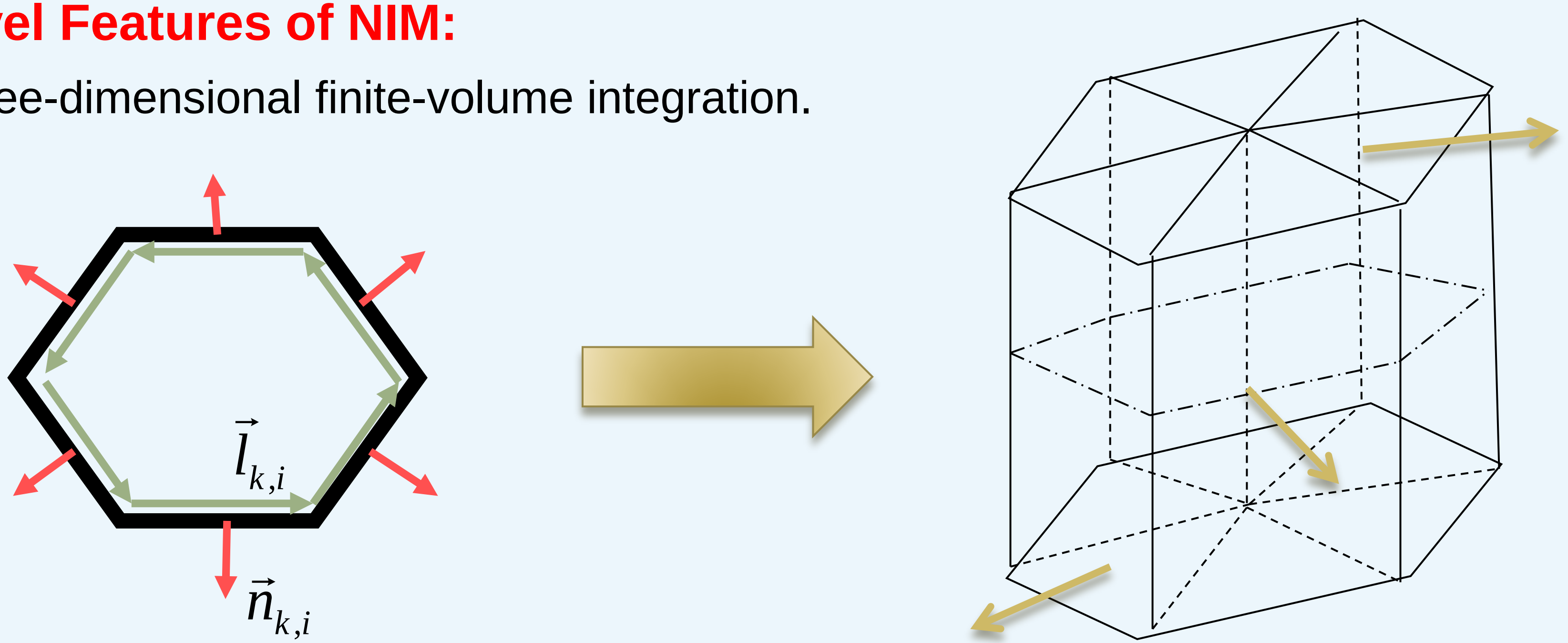
- **Efficient Indirect Addressing Scheme on Irregular Grid**
- **Grid Optimization for Efficiency and Accuracy**
- **Novel Features of NIM:**

-Three-dimensional finite-volume integration.

3-D control volume box



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  - Conservative flux formulation on height coordinate.

Flux form GEs on 3-D control volume on height coord.

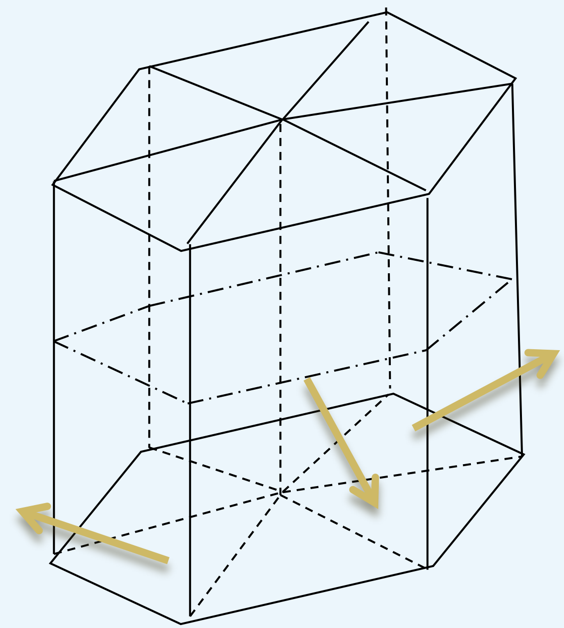
$$
\begin{cases}
\dfrac{\partial U}{\partial t}+\dfrac{\partial (Uu)}{\partial x}+\dfrac{\partial (Vu)}{\partial y}+\dfrac{\partial (Wu)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial x}= F_u \\
\dfrac{\partial V}{\partial t}+\dfrac{\partial (Uv)}{\partial x}+\dfrac{\partial (Vv)}{\partial y}+\dfrac{\partial (Wv)}{\partial z}+\gamma R\pi\dfrac{\partial \Theta'}{\partial y}= F_v \\
\dfrac{\partial W}{\partial t}+\dfrac{\partial (Uw)}{\partial x}+\dfrac{\partial (Vw)}{\partial y}+\dfrac{\partial (Ww)}{\partial z}+\left(\gamma R\pi\dfrac{\partial \Theta'}{\partial z}-\overline{\rho}g\dfrac{\pi'}{\overline{\pi}}+\rho' g\right)=0 \\
\dfrac{\partial \rho}{\partial t}+\dfrac{\partial (U)}{\partial x}+\dfrac{\partial (V)}{\partial y}+\dfrac{\partial (W)}{\partial z}=0. \\
\dfrac{\partial \Theta}{\partial t}+\dfrac{\partial (U\theta)}{\partial x}+\dfrac{\partial (V\theta)}{\partial y}+\dfrac{\partial (W\theta)}{\partial z}=\dfrac{\Theta\dot{H}}{C_p T} \\
\dfrac{\partial (\rho q)}{\partial t}+\dfrac{\partial (Uq)}{\partial x}+\dfrac{\partial (Vq)}{\partial y}+\dfrac{\partial (Wq)}{\partial z}=S_q
\end{cases}
$$

$$(U,V,W,\Theta,\rho)=(\rho u,\rho v,\rho w,\rho\theta,\rho);\quad \Theta(x,y,z,t)=\overline{\Theta}(z)+\Theta'(x,y,z,t)$$

$$\rho(x,y,z,t)=\overline{\rho}(z)+\rho'(x,y,z,t);\qquad \nabla p=\gamma R\pi\nabla\Theta$$

$$p=p_0\left(\frac{R\Theta}{p_0}\right)^{\gamma};\quad \pi=\left(\frac{p}{p_0}\right)^{\kappa}$$

3-D control volume box



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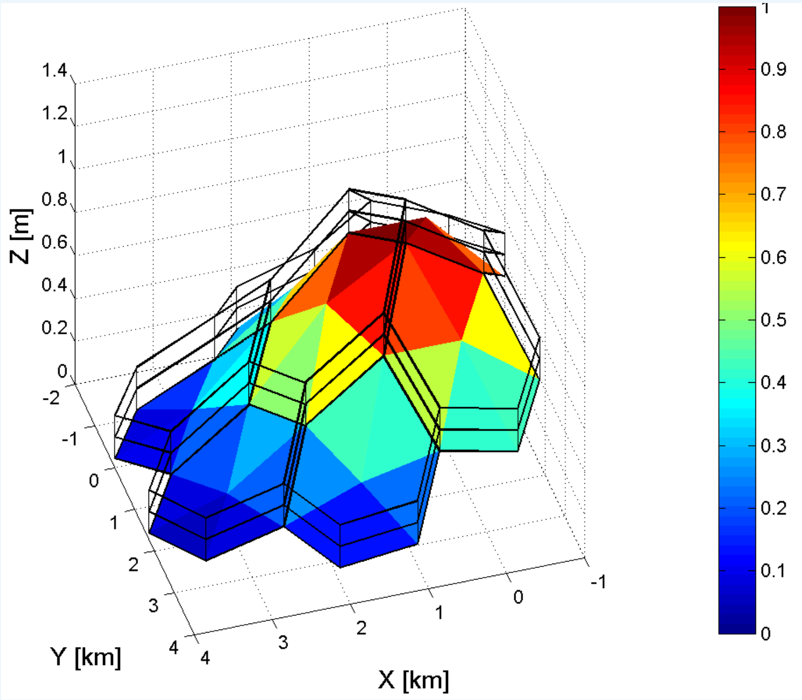
  - 3-D volume Integration to calculate PGF.



Various PGF treatments over topography

$$\frac{\partial p}{\partial x} \sim \frac{\partial p}{\partial x'} - z_{x'} z_z' \frac{\partial p}{\partial z'}$$

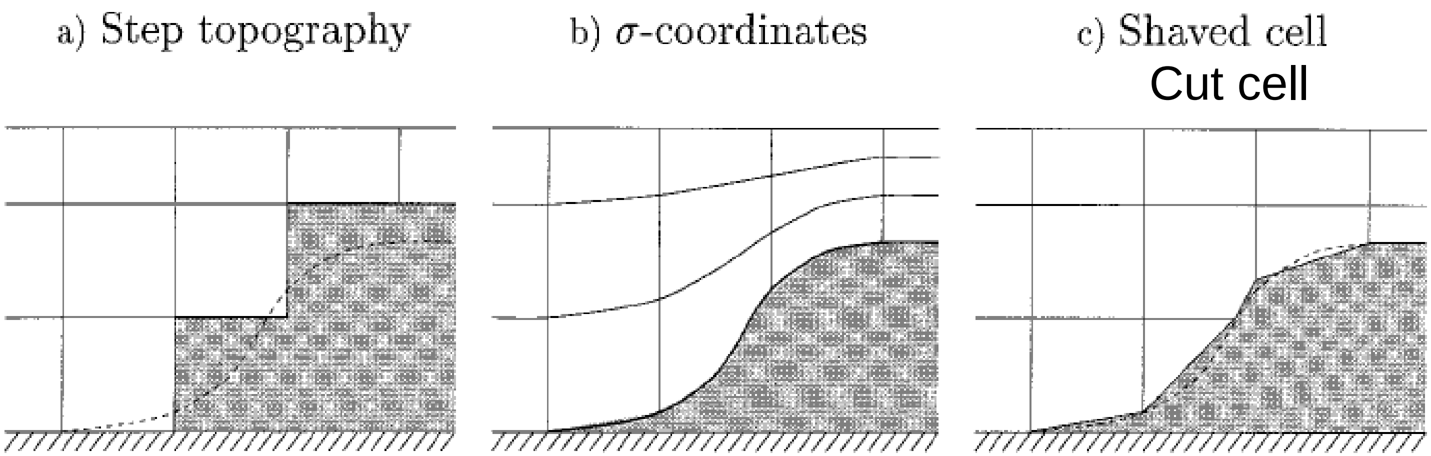
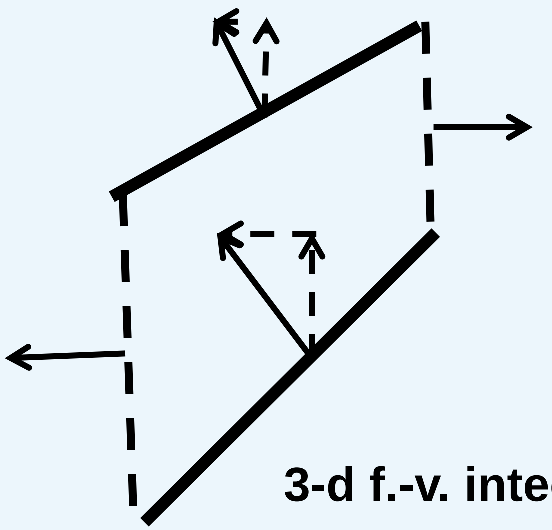


FIG. 1. The representation of a smoothly varying bottom (dashed line) in (a) a height coordinate model using step topography, (b) a terrain-following coordinate model, and (c) a height coordinate model with piecewise constant slopes.

** A. Adcroft, etal., Mon. Wea. Rev. 125, 2293–2315.*



3-d f.-v. integration over topography

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  - Horizontal explicit, vertical implicit (HEVI).

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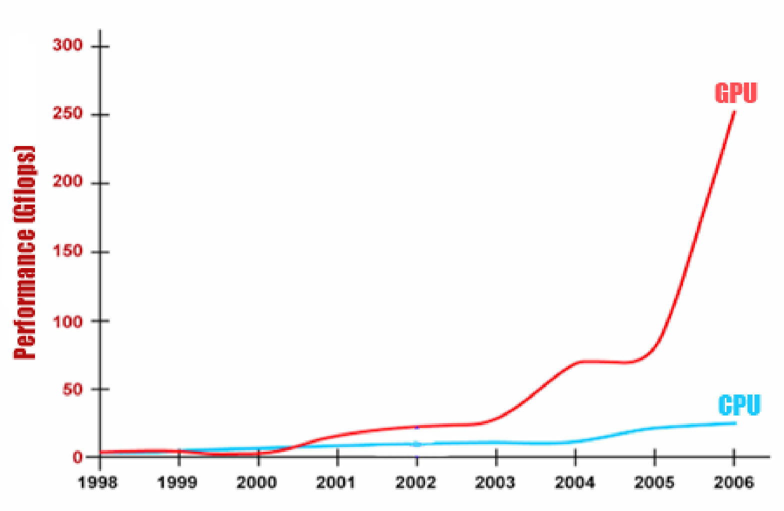
  - Fast GPUs to speed up calculation.

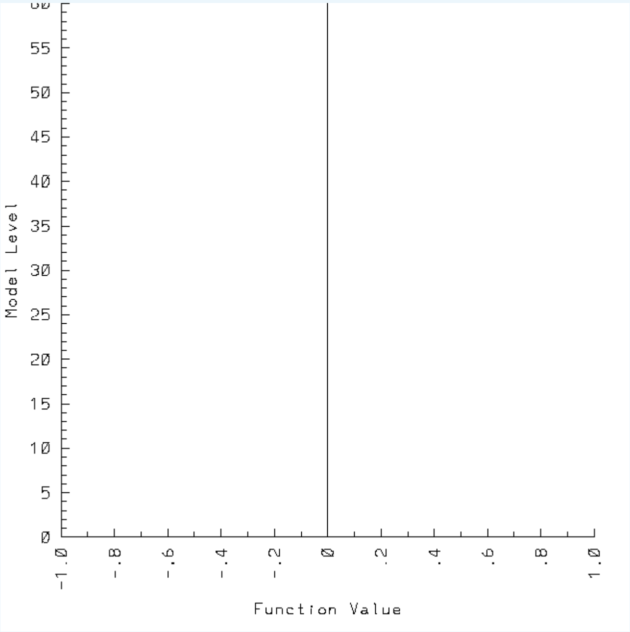


NIM benchmarks test cases

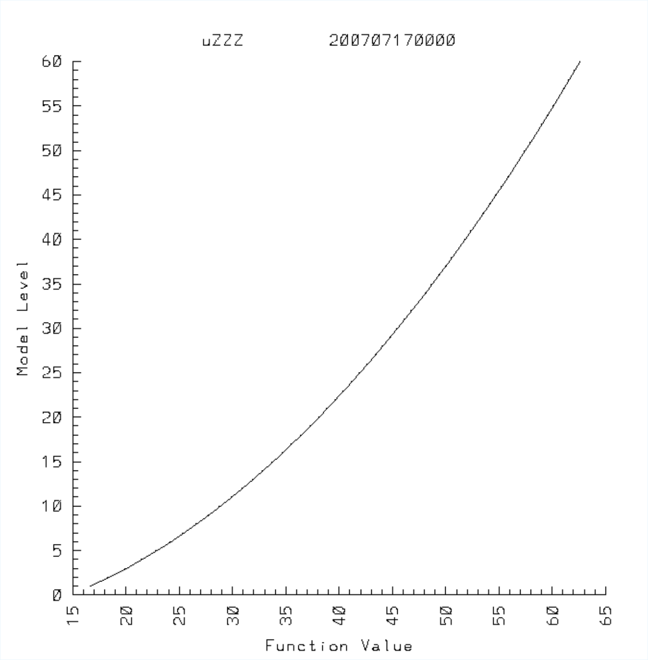
heat forced circulation (Cartesian)
warm bubble (Cartesian)
density current (Cartesian),
linear mountain waves (Cartesian),
Internal gravity waves (**DCMIP:**Icos-grid)
mountain waves (**DCMIP:**Icos-grid)
tropical cyclone (**DCMIP:**Icos-grid)
baroclinic waves (**DCMIP:** in progress)
multi-months aqua-planet simulations (Icos-grid)

Vertical Zonal Wind Shear in DCMIP mountain wave cases

Case 2.1

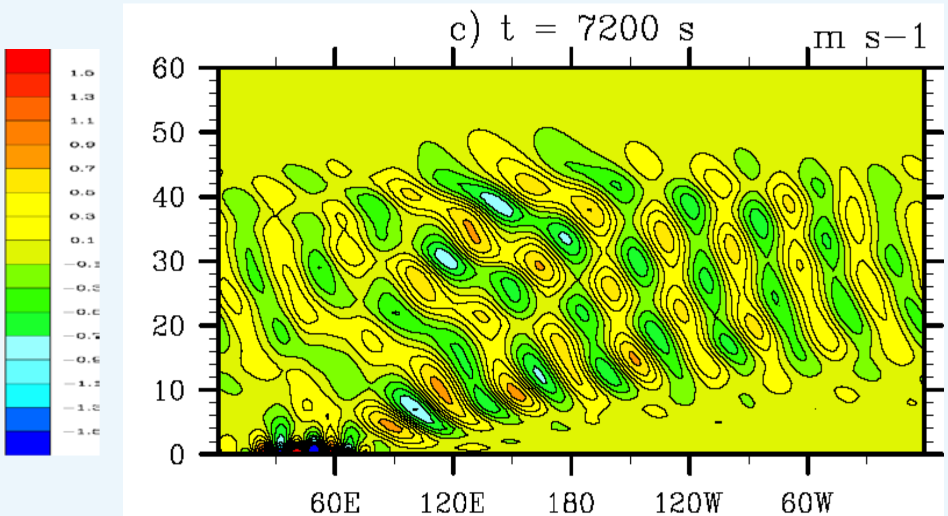


Case 2.2

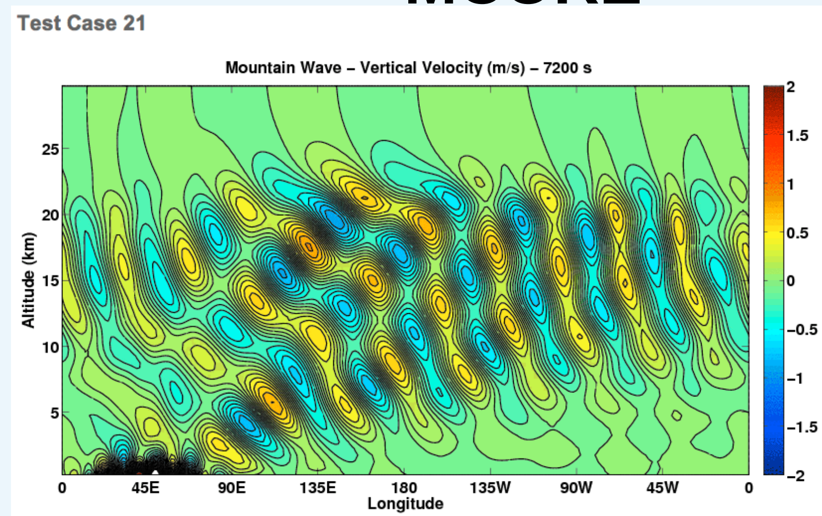


DCMIP: 2.1 (small earth, X=500, dz=500m)

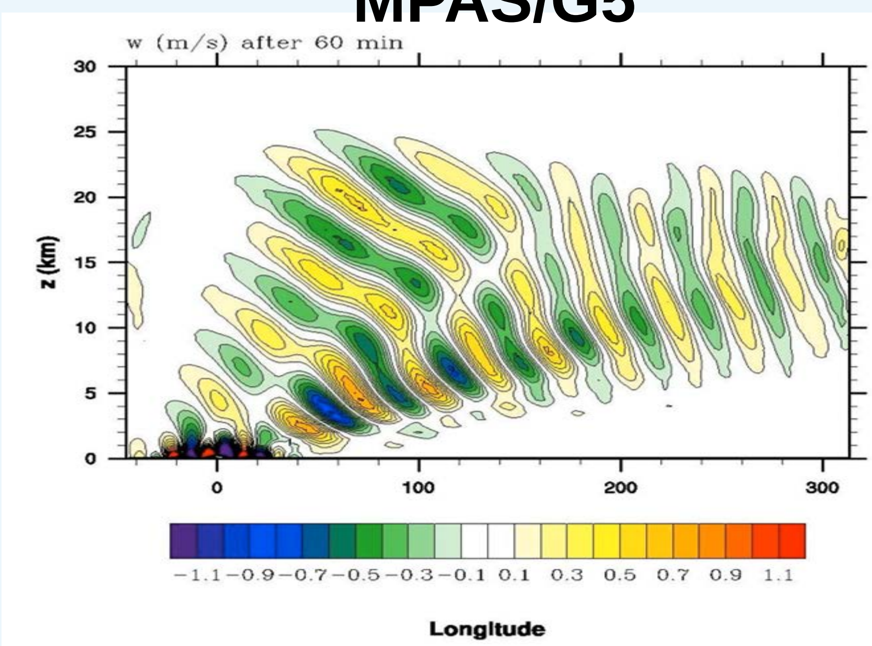
Endgame



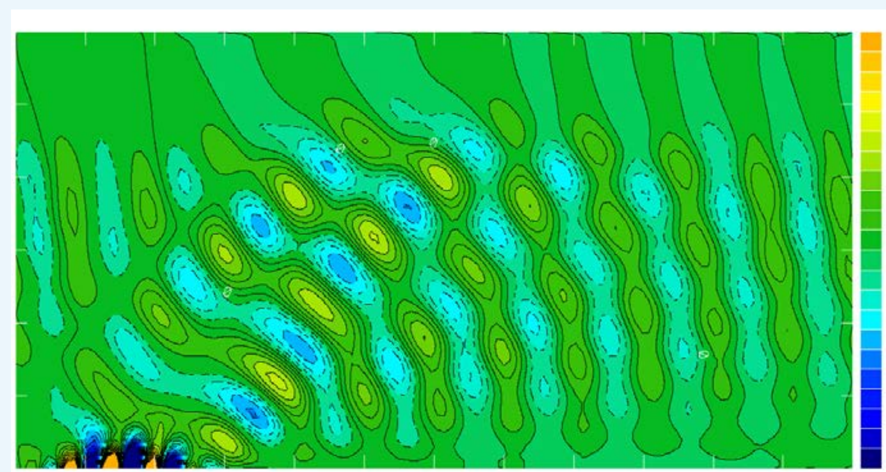
MCORE



MPAS/G5

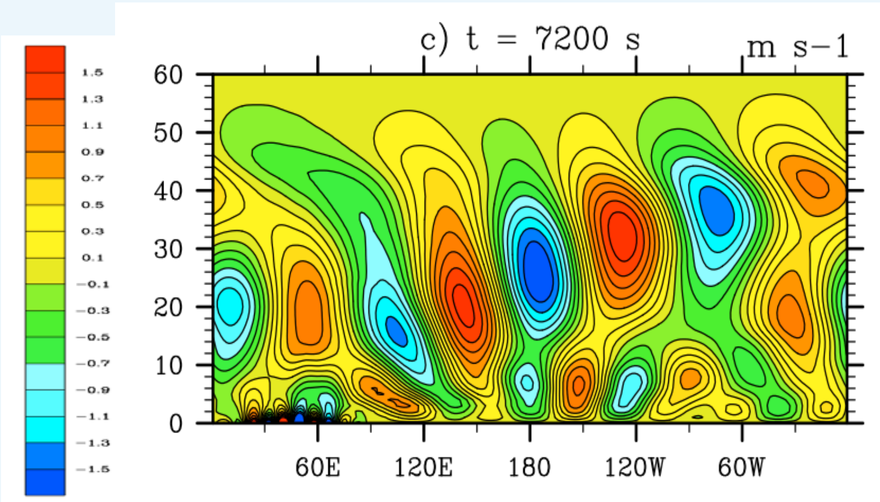


NIM/G5



DCMIP: 2.2 (small earth)

Endgame



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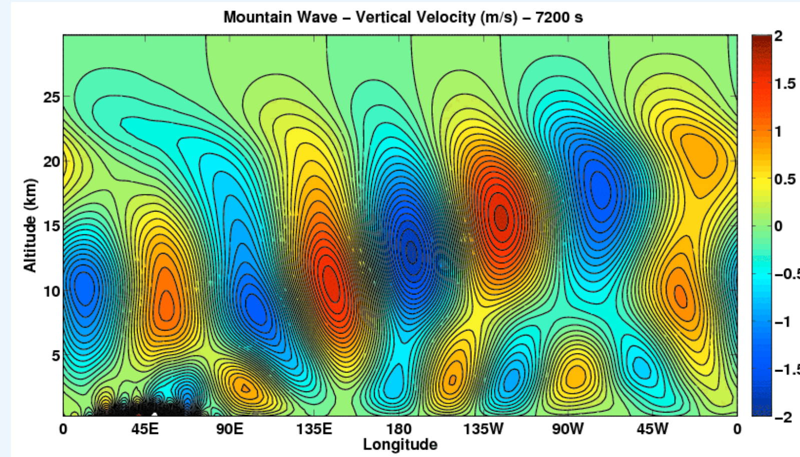
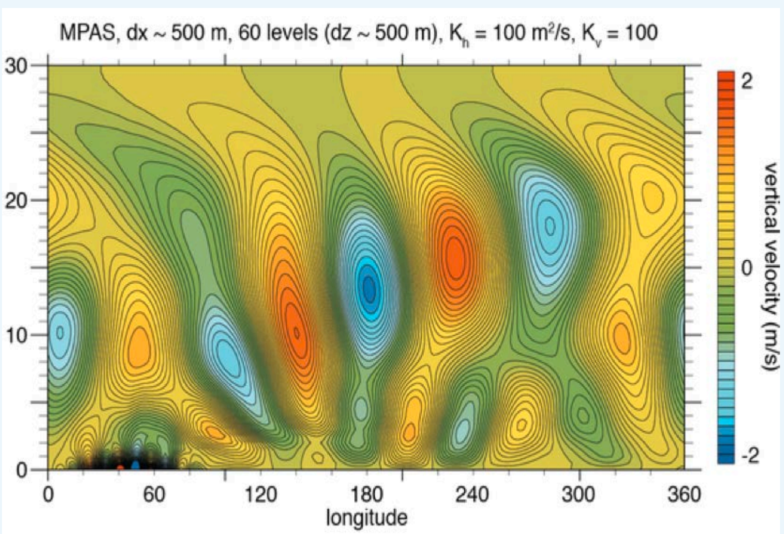
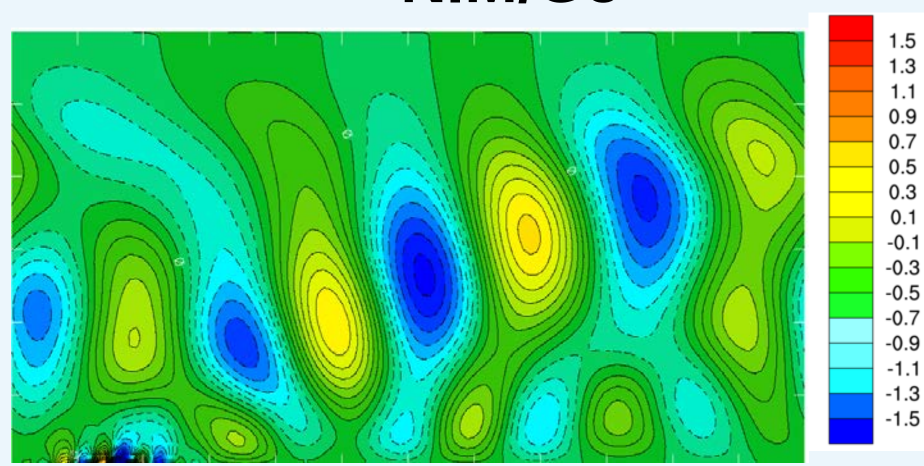


MPAS/G5

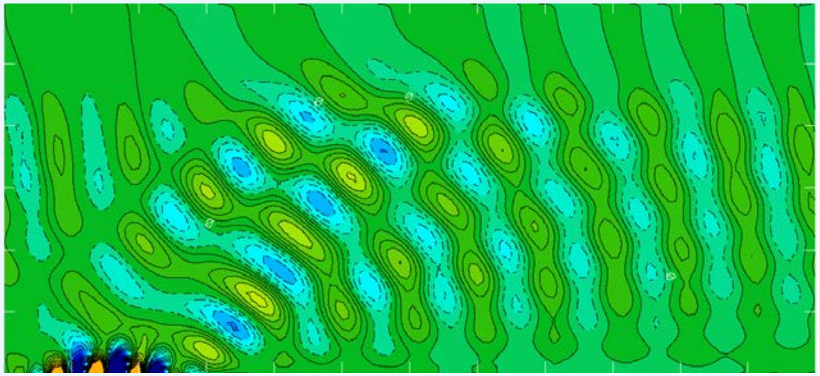


NIM/G5

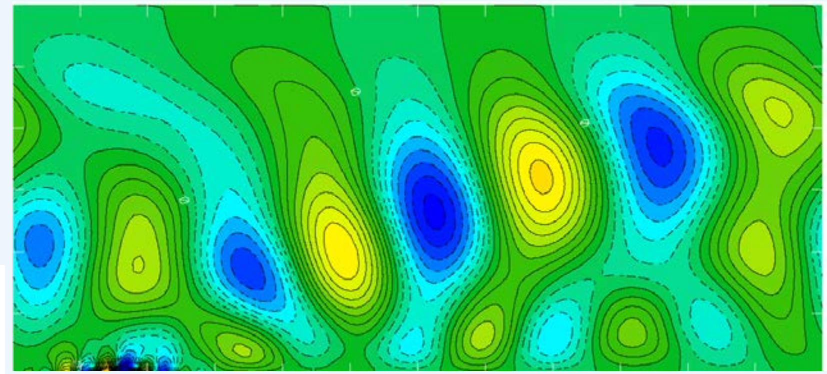


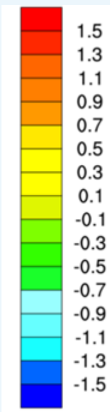
DCMIP: case 2 (small earth)
NIM: resolution Sensitivities

No shear case, dz = 500 m

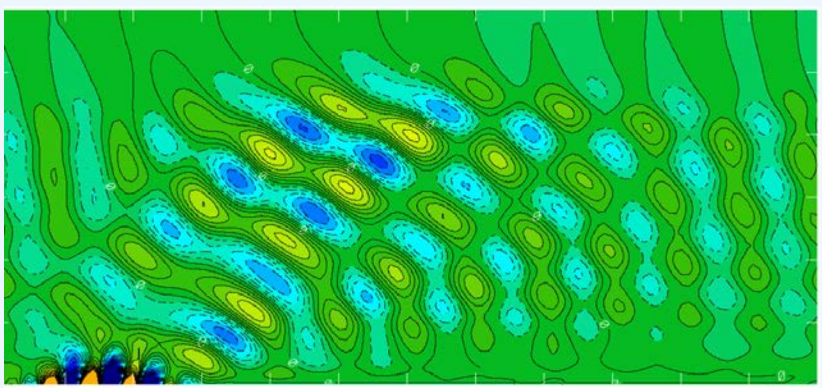


Shear case, dz = 500 m

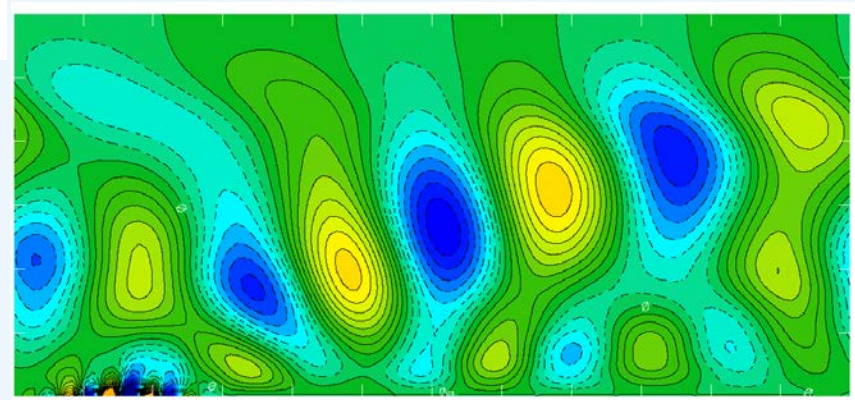




No shear case, dz = 250 m

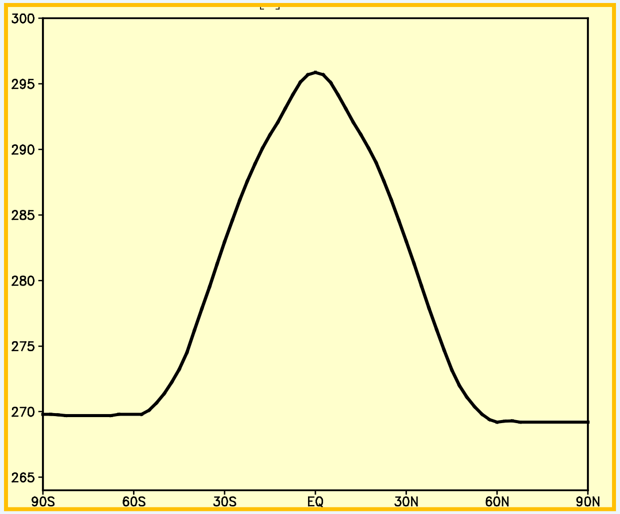


Shear case, dz = 250 m



Physics packages
&
aqua-plan et simulations

Aqua-Planet Simulation

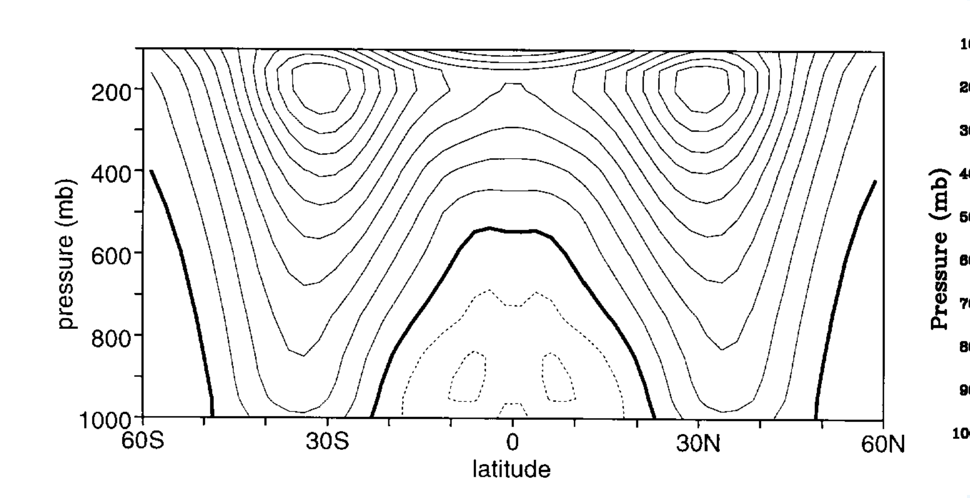


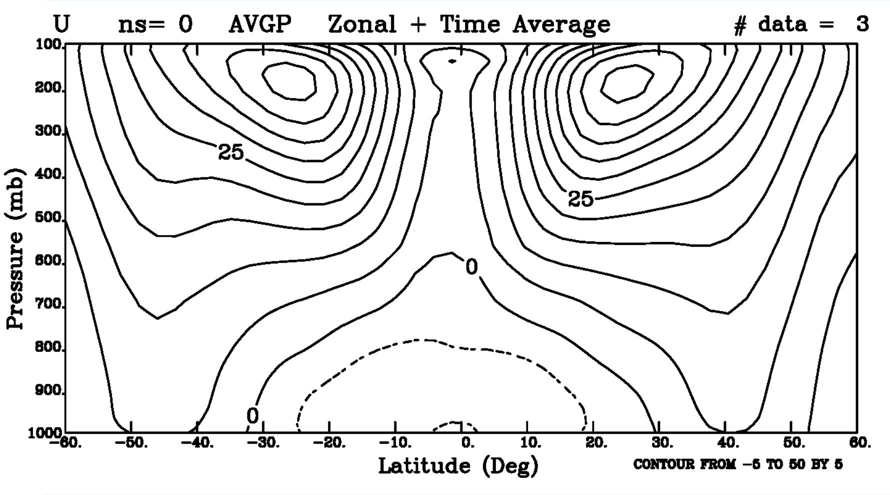
NIM 800-day aqua-planet simulation	
MODEL	NIM/GFS NIM/GRIMs
SST	Zonally uniform, max. temp. on equator
Resolution	G5 (Δx ~ 240 km)
Vertical	32 Stretch layers
Model top	25 km
Δt	20 min

NIM aqua-planet simulation

Hoskins et al. (1999), Tellus

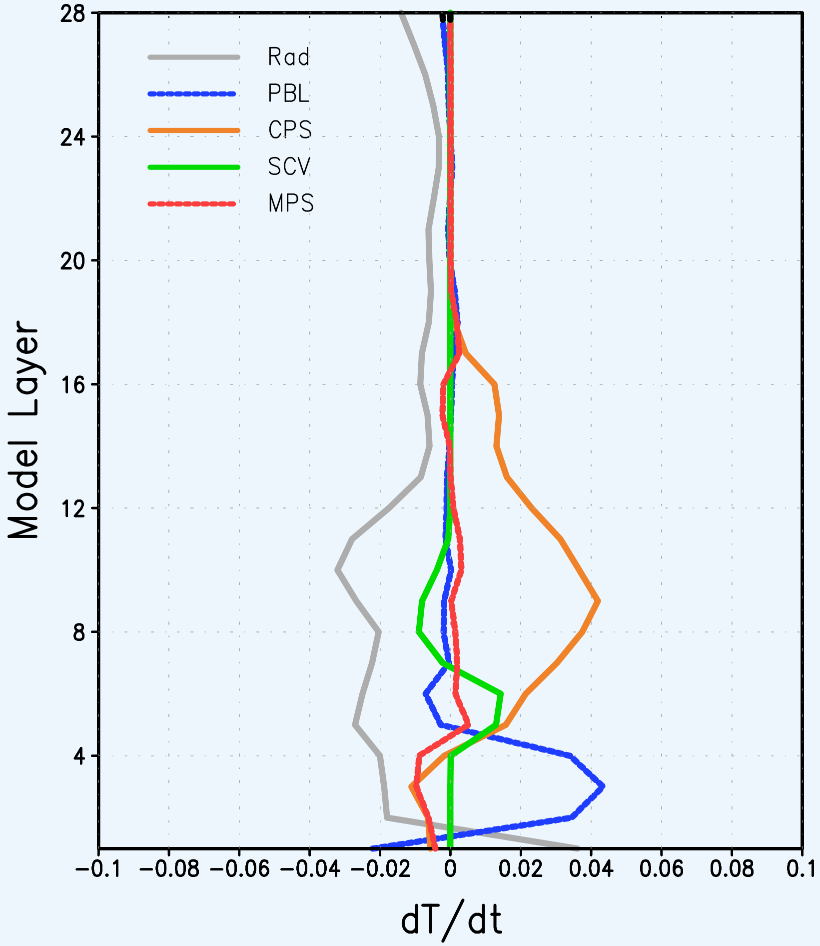
NIM mean zonal wind



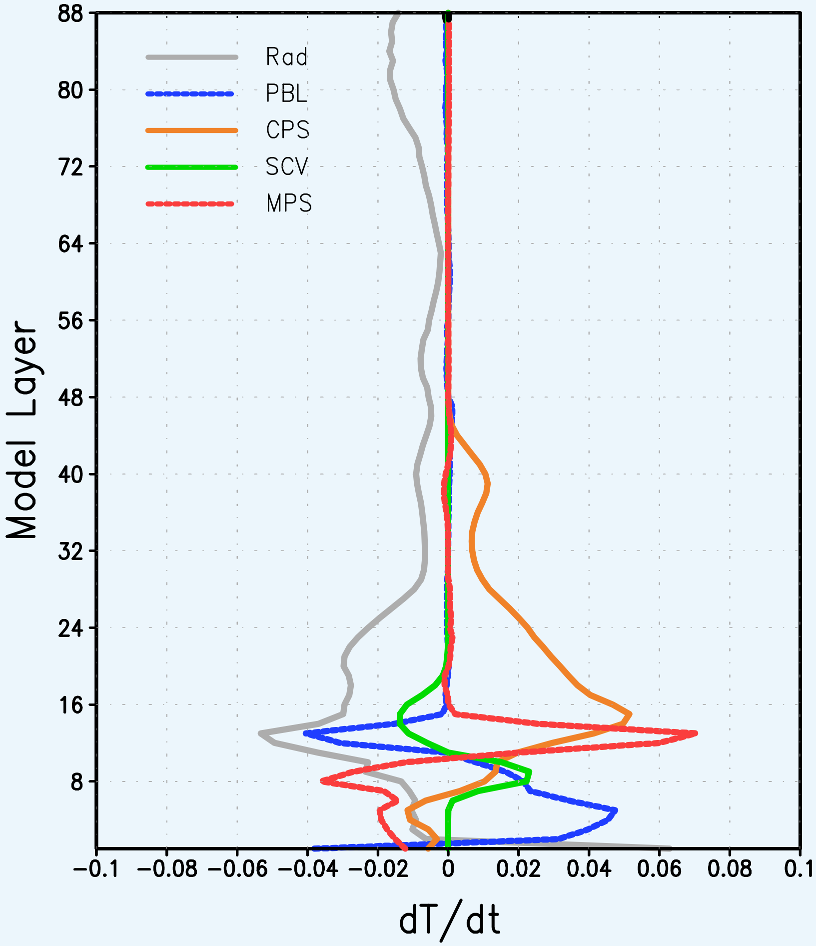


T Tendency from physics (K/6hr)

G6K32



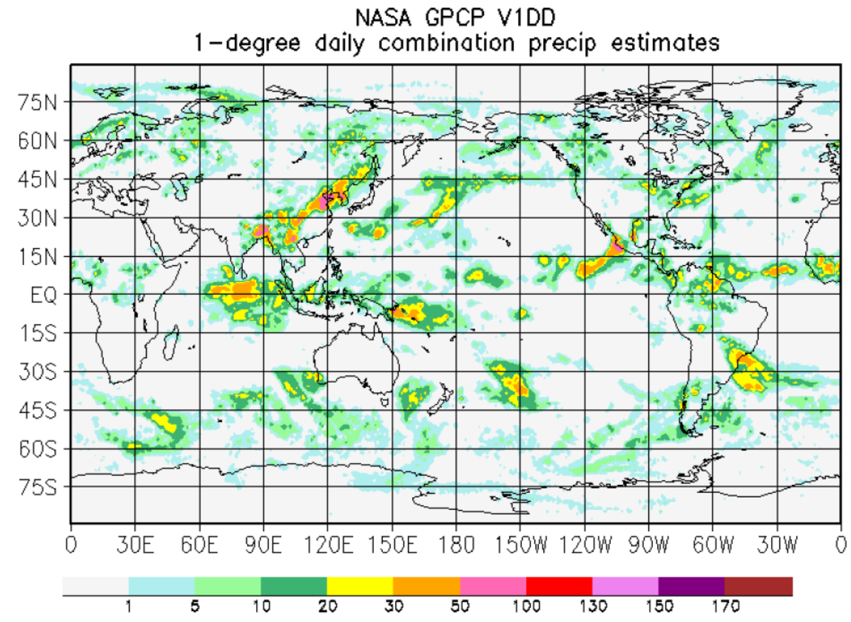
G6K96



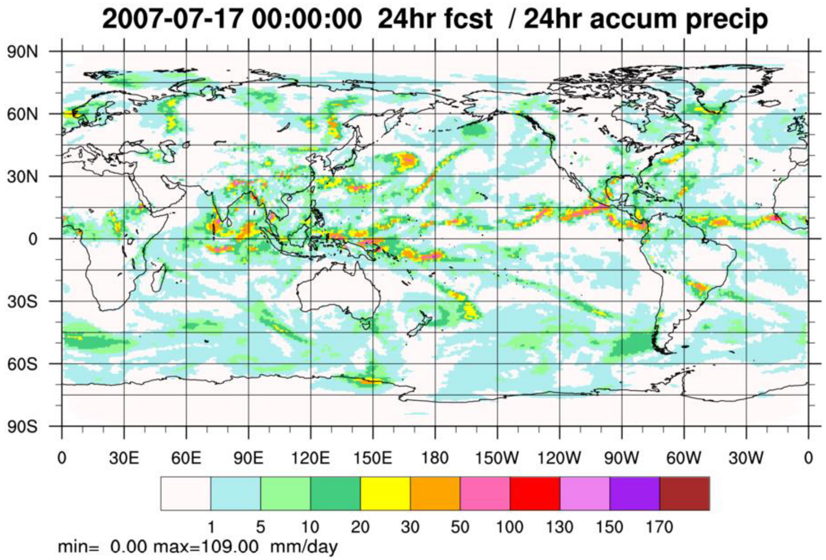
NIM real data simulation initialized with GFS initial condition (comparisons of precipiation fcsts)

- Interpolate GFS initial data to Icosahedral grid.
- Perform hydrostatic initialization.
- Perform 10-day fcsts on G6 grid (~120km) and 56 layers.
- Use GFS terrain & sfc parameters, physics package .
- Precipitation comparison

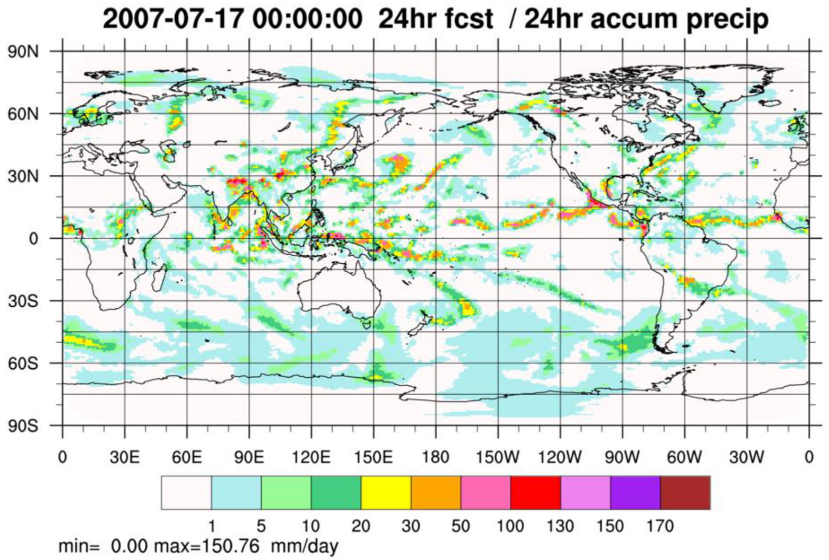
DAY1



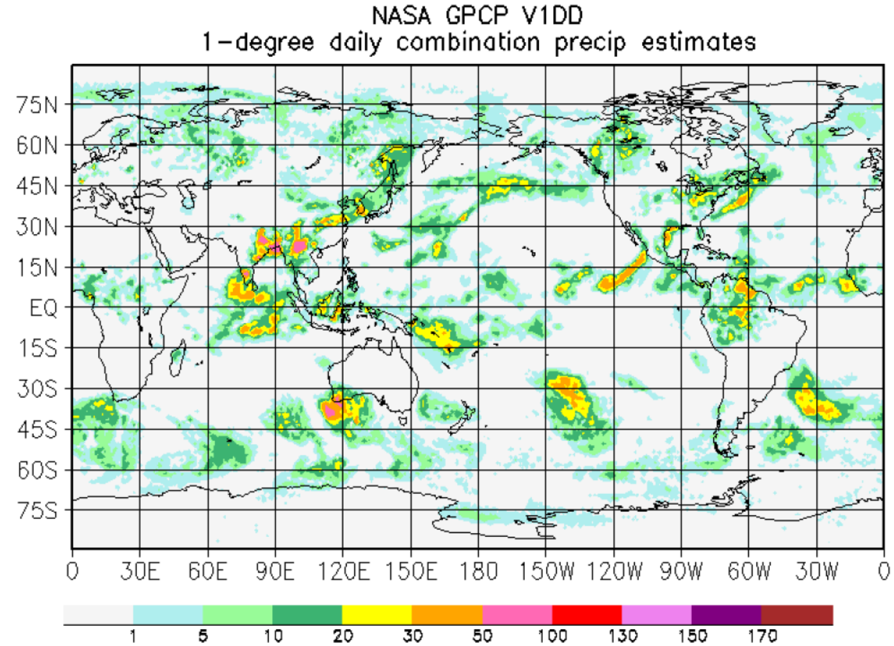
FIM G06



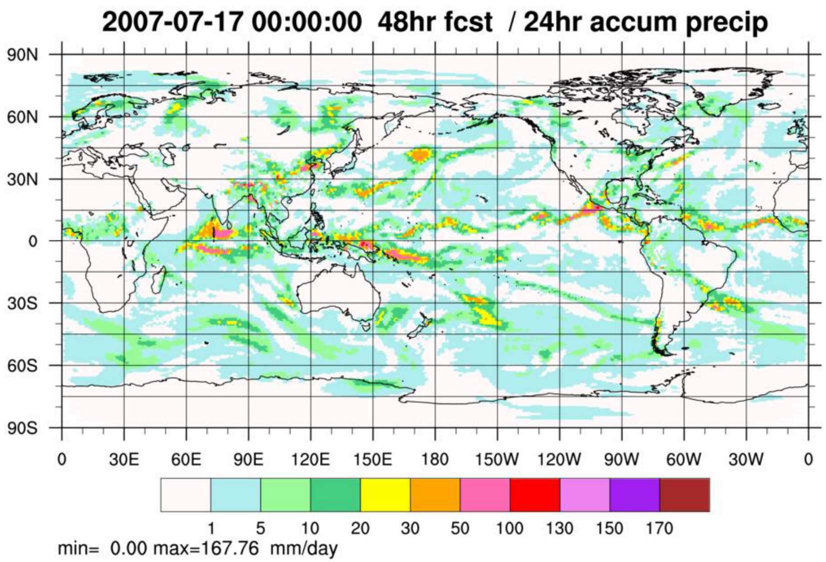
NIM G06



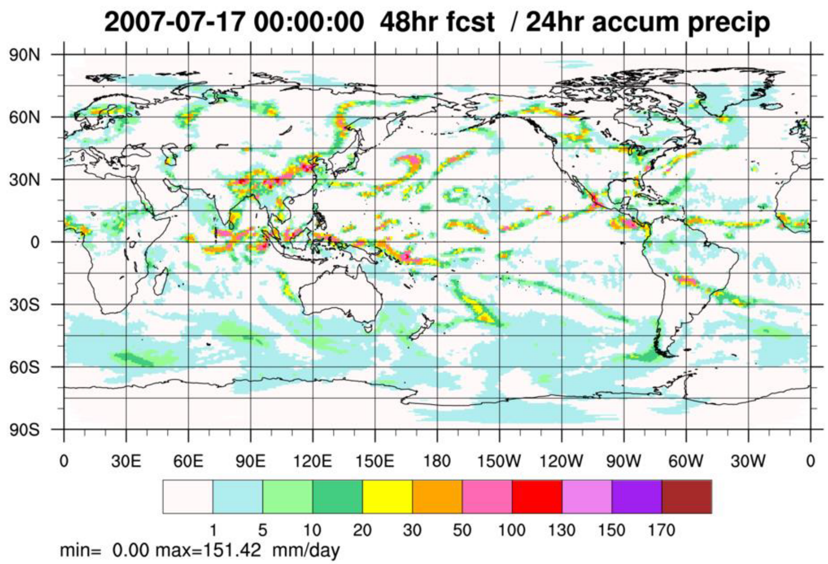
DAY 2



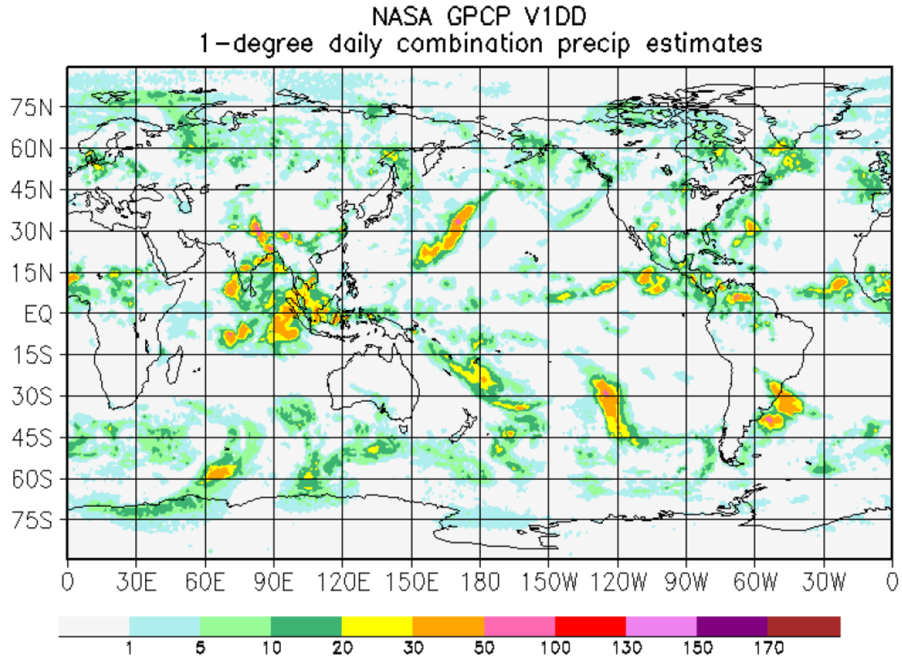
FIM G06



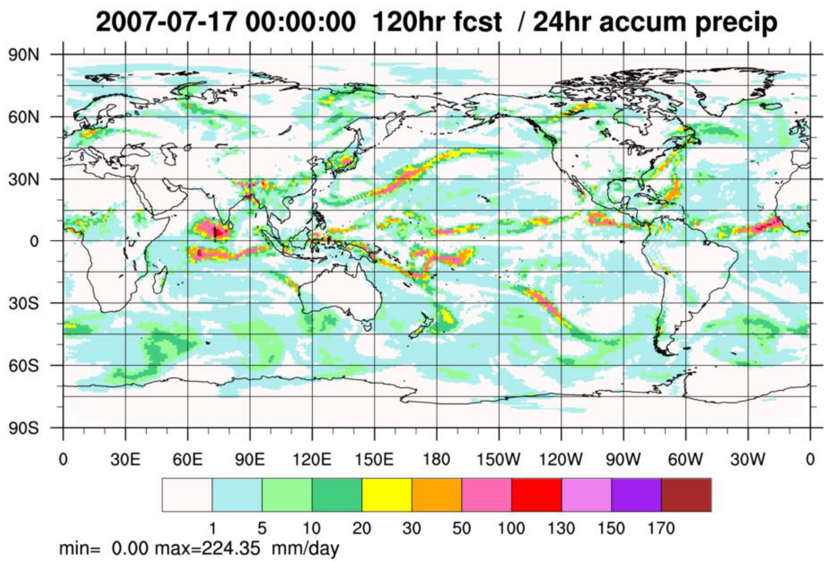
NIM G06



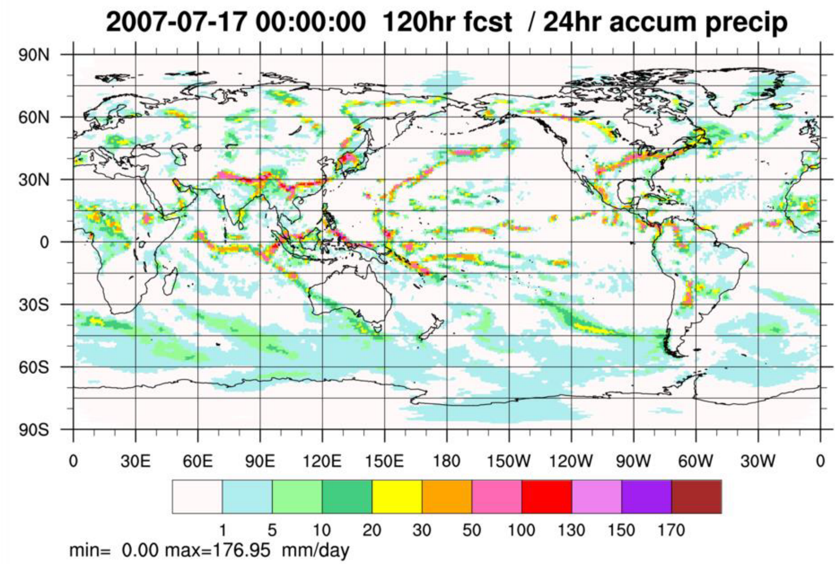
DAY 5



FIM G06



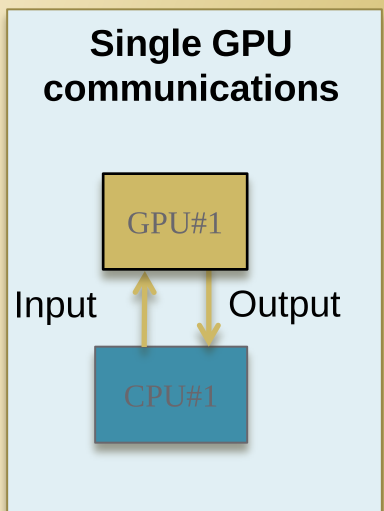
NIM G06



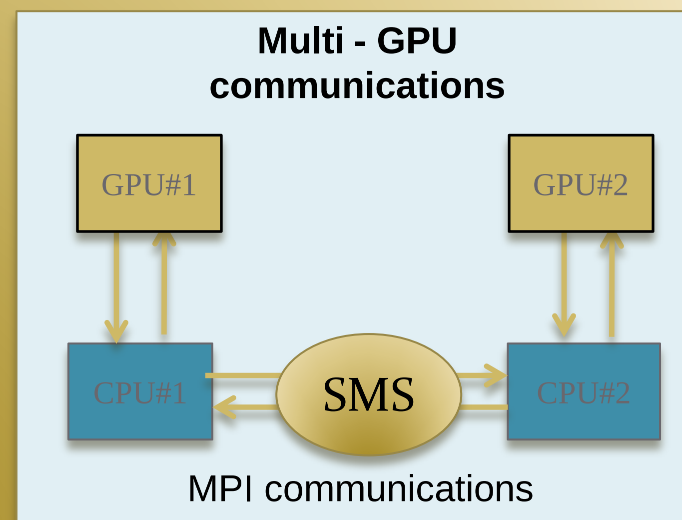
NIM/GPU implementation (fine grain parallization)

Mark Govett, Tom Henderson,
Jacques Middlecoff, Jim Rosinski

- NIM was implemented on CPU and GPU Architectures
  – Code converted to CUDA using the F2C-ACC compiler we developed
  – NIM used by vendors (PGI,CAPS) to benchmark commercial GPU compilers



– Serial Performance
– Parallel Performance
- Maintain single source code



2013: CPUs vs. GPUs

6-core Westmere CPU	8-core Opteron CPU	8-core Sandybridge CPU	C2050 Fermi GPU	K20X Kepler GPU
86.8	143.0	60.3	25.1	20.7

- Short time period runs
  - I/O ***not*** included
- Only limited performance tuning on Opteron and Kepler thus far (gaea)
- “One socket” of each technology

Final remarks and Outlook

- **A 3-D f.-v. Nonhydrostatic Icosahedral Model (NIM) has been developed and tested w/ benchmarks,**
- **3-D f.-v. integration calculates PGF over topography with 3-D control volume integration,**
- **Incorporated GFS, GRIMs, MPAS physics into NIM modeling systems,**
- **NIM for medium-range weather forecasts at < 10-km resolution with large numbers of vertical layers to improve HIWP.**

A potential postdoctoral position in dynamical core research area
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