Nonhydrostatic Icosahedral Model (NIM)
A 3-D finite-volume NIM

Jin Lee
(+ other contributors)

Earth System Research Laboratory (ESRL)

NOAA/OAR

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

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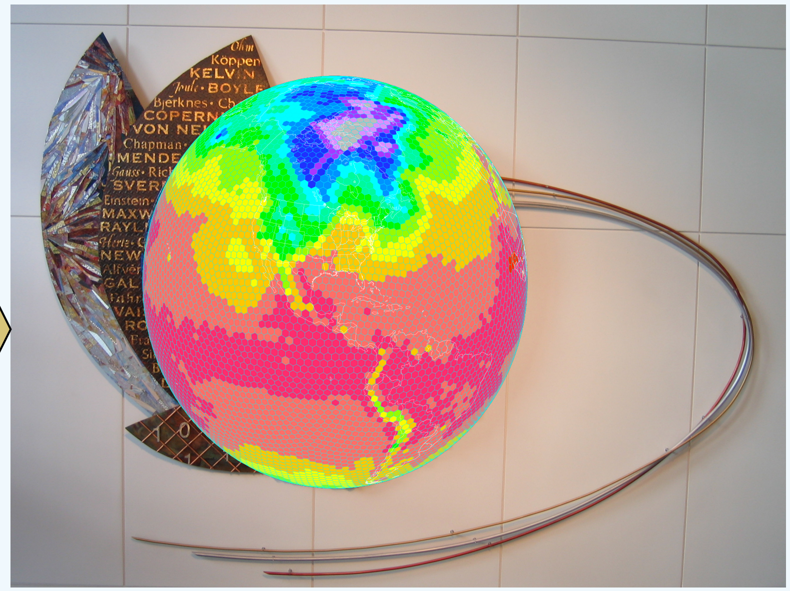


Chemical Sciences Div
Global Monitoring Div
Physical Sciences Div
Global Systems Div

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

ESRL finite-volume Icos- models (FIM/NIM)

ESMF

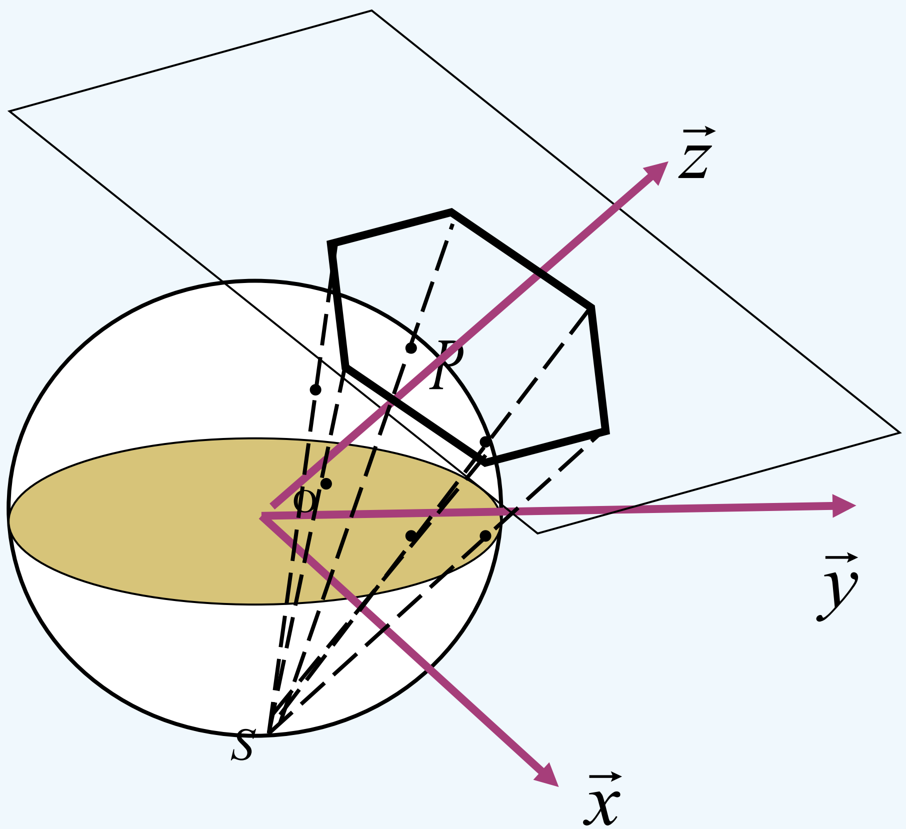
- **FIM (flow-following finite-volume Icosahedral model):**
- **Target resolution ≥ 10 km**
- **A hydrostatic model consists of 2-D finite-volume SWM coupled with hybrid σ-θ vertical solver.**
- **Produce accurate medium-range weather forecasts**

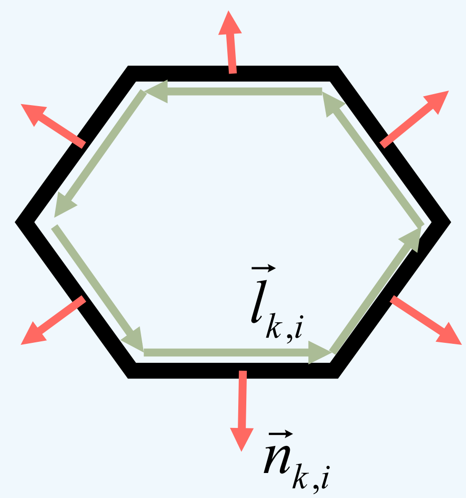
- **NIM (Nonhydrostatic Icosahedral model):**
- **Target resolution : O(1 km) and beyond**
- **Extension of 2-D finite-volume integration into 3-D integration on control volume defined on the height coordinate.**
- **Use the latest GPU technology to speed up high-resolution model calculations.**

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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- **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.

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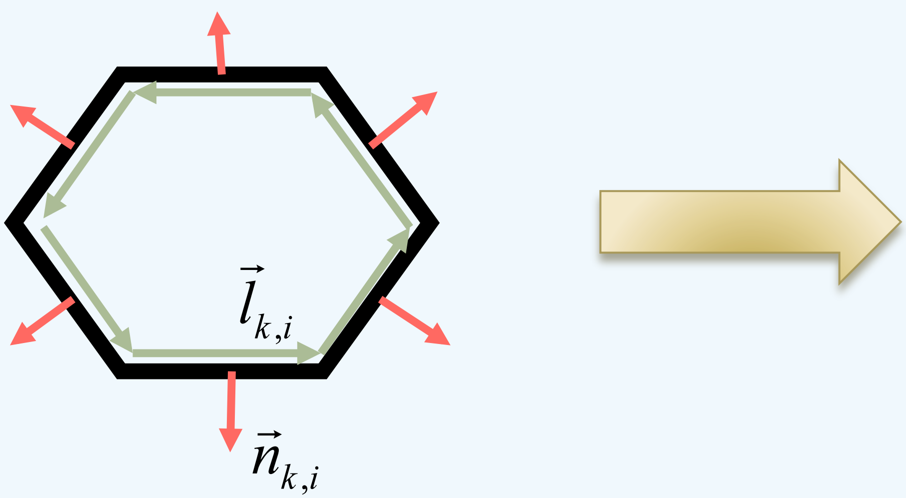
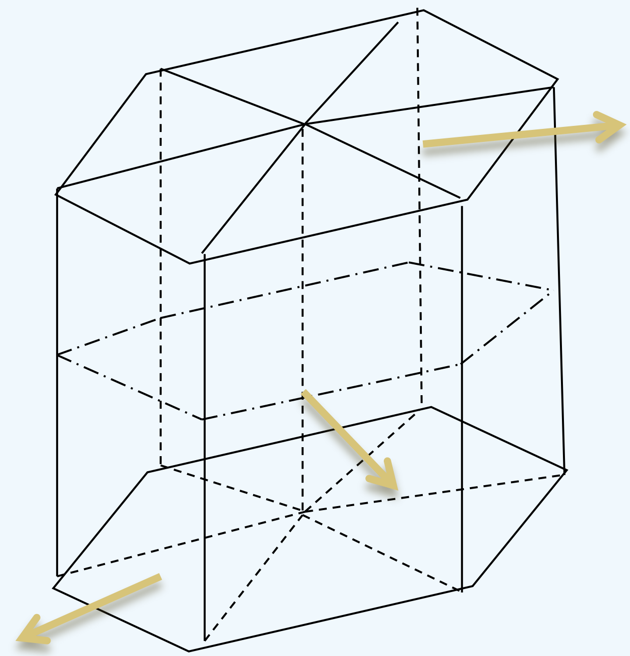
  -Three-dimensional finite-volume integration.

3-D control volume box





Vorticity theorem :

$$\varsigma = \int_A \left(\nabla_h \times \vec{V}_h\right) dA = \oint_s \left(\vec{V}_h \cdot \vec{l}\right) ds$$

Divergence theorem :

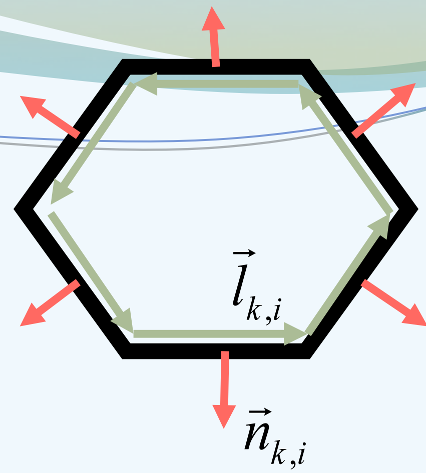
$$\int_A \left(\nabla_h \cdot \vec{V}_h \phi\right) dA = \oint_s \left(\vec{V}_h \phi \cdot \vec{n}\right) ds$$

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

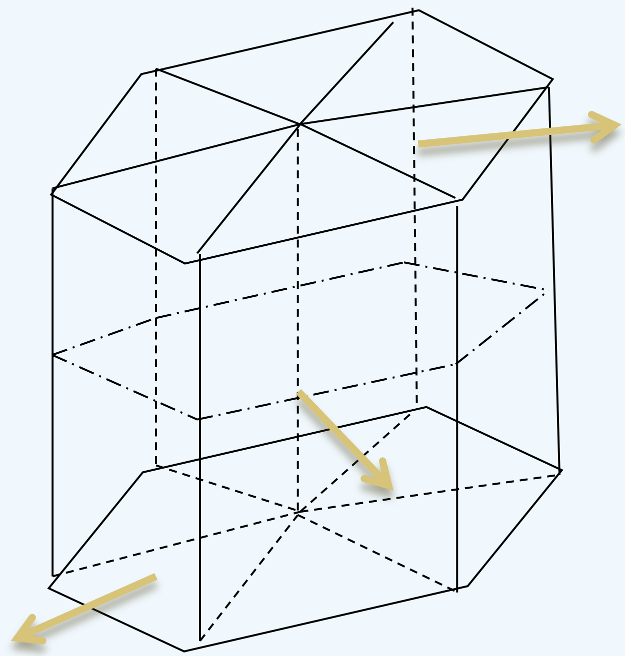
$$(U, V, W, \Theta, \rho) = (\rho u, \rho v, \rho w, \rho \theta, \rho); \quad \Theta(x,y,z,t) = \overline{\Theta}(z) + \Theta'(x,y,z,t)$$

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

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



3-D control volume box



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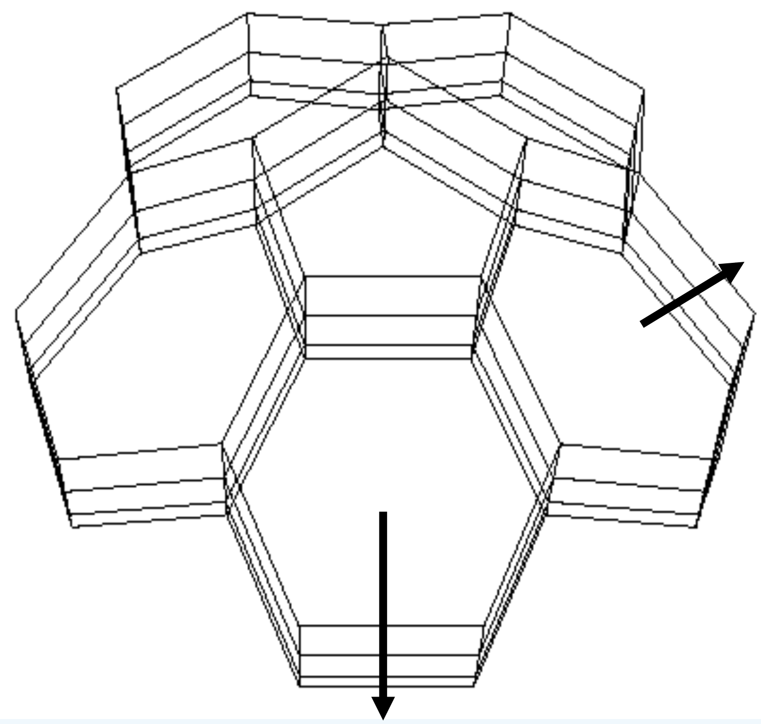
- **Novel Features of NIM:**

  -Three-dimensional finite-volume integration.

  -3-D volume Integration to calculate
  pressure gradient force (PGF)



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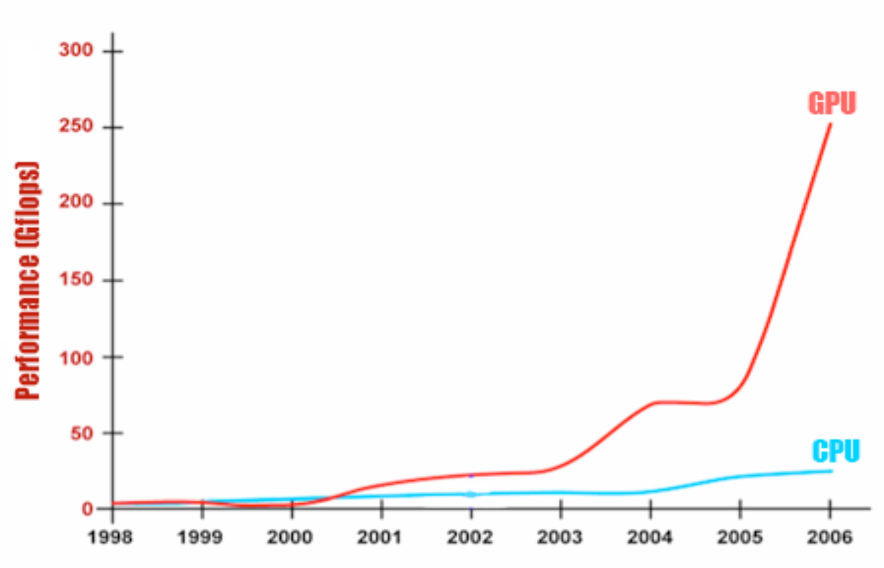


NIM/GPU implementation

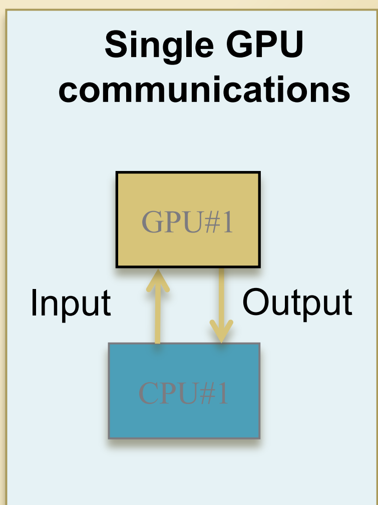
- **CPU**
  - **Bigger Systems**
  - **More Expensive Facilities**
  - **Bigger Power Bills**
  - **Lower System Reliability**

- **GPU**
  - **10-20 times faster**
  - **10x less power**
  - **10x lower cost**

– NIM was implemented on CPU and GPU Architectures

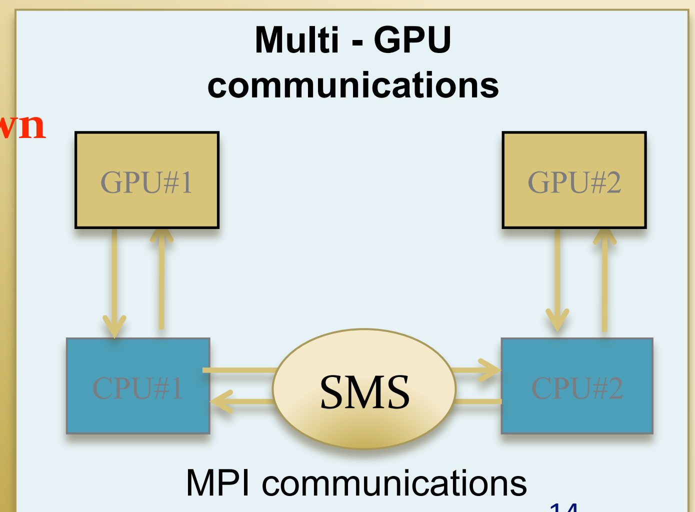
– Code converted to CUDA using the F2C-ACC compiler we developed

– NIM used by vendors (PGI,CAPS) to benchmark commercial GPU compilers



– Serial Performance
- 2009: 34x Tesla / Harpertown
- 2010: 20x Fermi / Nehalem

– Parallel Performance
- 2010: 15x with MPI communications



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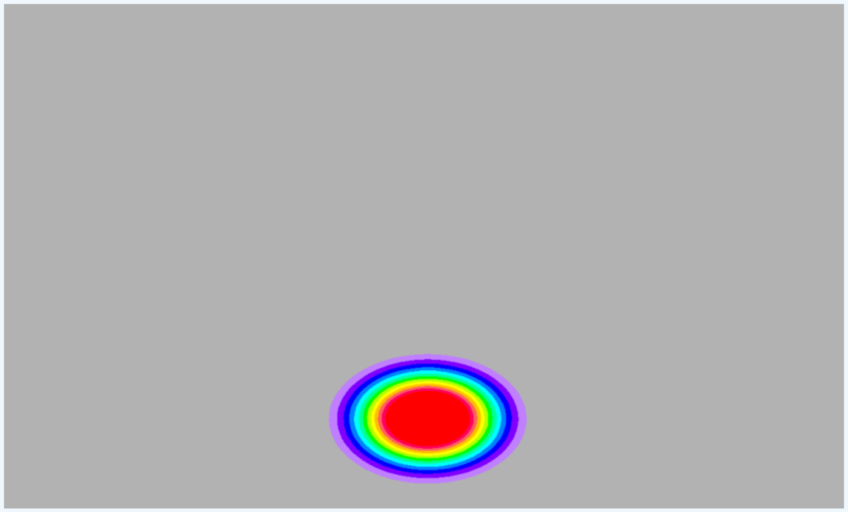
- Use fast GPUs to speed up calculations
- Runge-Kutta (RK)-4th for time discretization and
- Horizontal explicit, semi-implicit tri-diagonal solver for vertically propagating acoustic waves.

NIM mesoscale 2-D (X-Z) test cases:
(in 3-D model frame work)

heat forced circulation,
warm bubble,
density current,
mountain waves

Explicit .vs. Implicit tri-diag solvers

θ' **t= 0.0 min**



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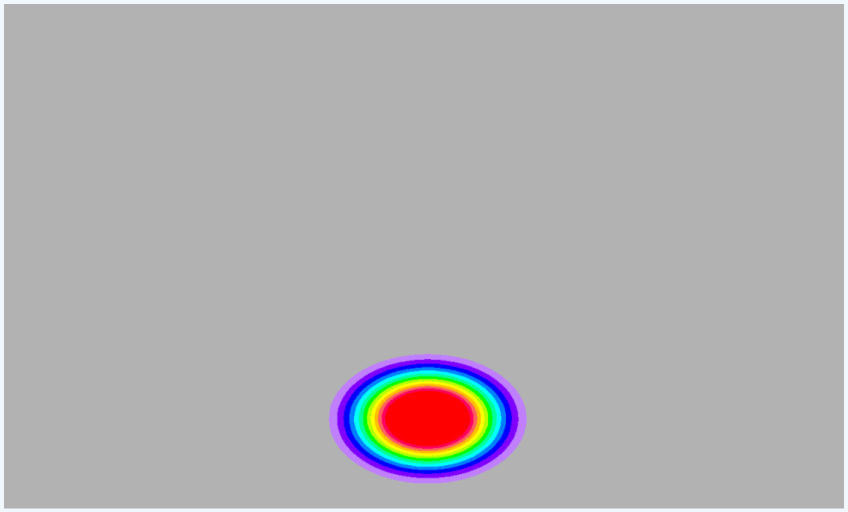
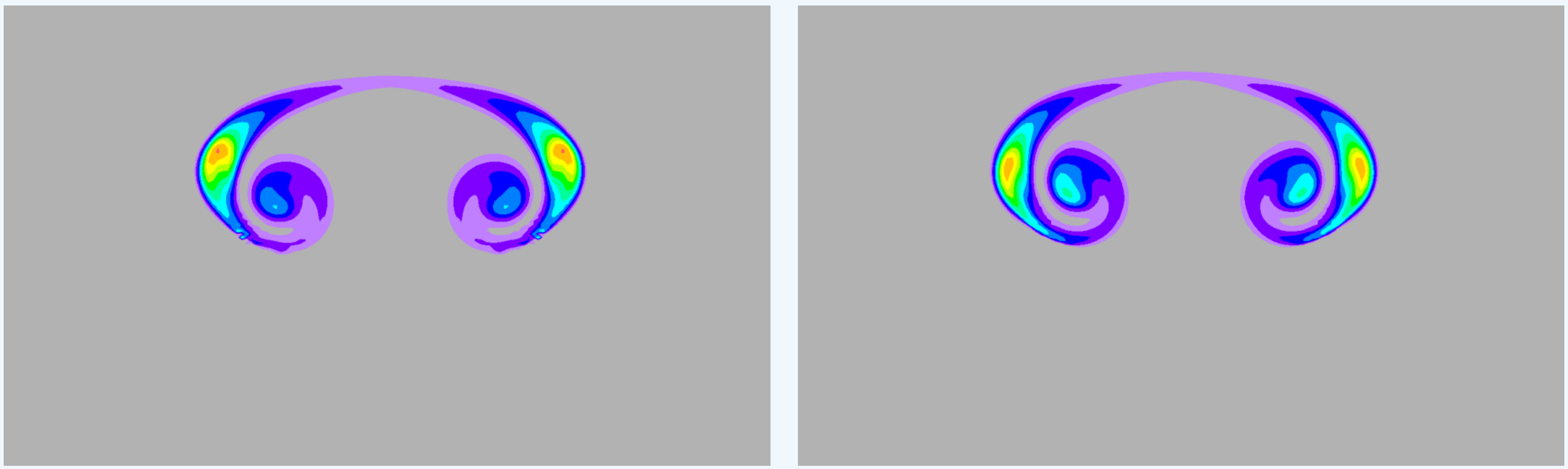


Explicit .vs. Implicit tri-diag solvers

θ' t= 14.0 min θ' t= 14.0 min



Icosahedral grid-stagger issues

A-grid ? C-grid ? Z-grid ? ….

Jin Lee, Wen-Yih Sun, A.E. MacDonald

CONCLUSION: NO PERFECT ICOS-GRID STAGGERING.

NIM 800-day aqua-planet simulation

Model configurations :

NIM/GRIMS, NIM/GFS

SST foced circulation

Resolution : G5 ($\Delta x \sim 240$km)

32 – vertical stretch layers

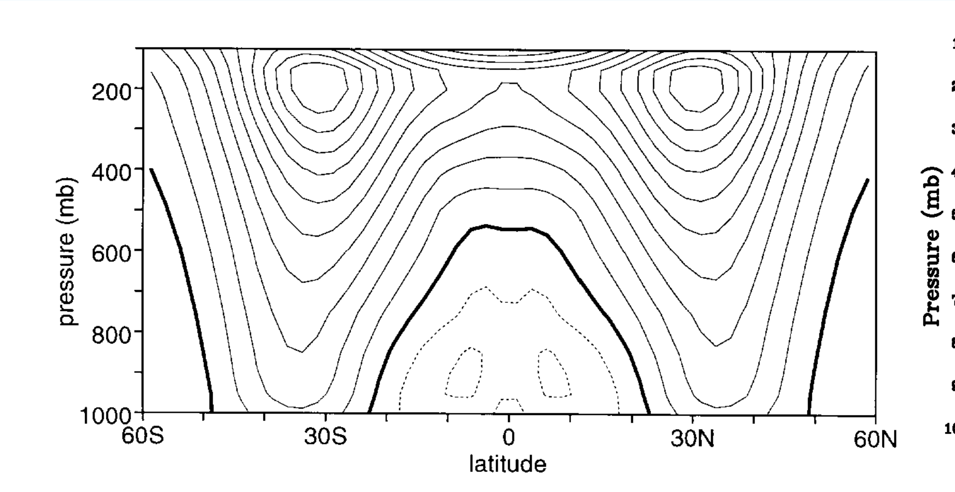
model top : 25 km

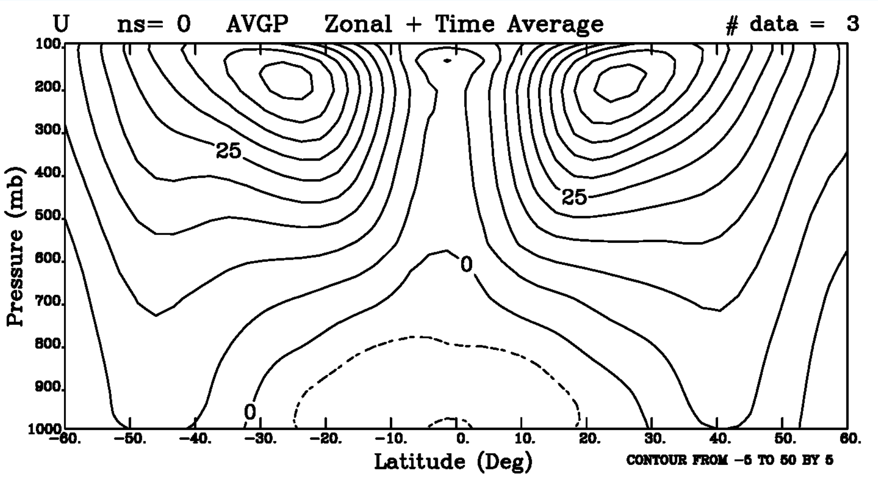
$\Delta t = 20\,\mathrm{min}$

NIM aqua-planet simulation

Hoskins et al. (1999), Tellus

NIM mean zonal wind

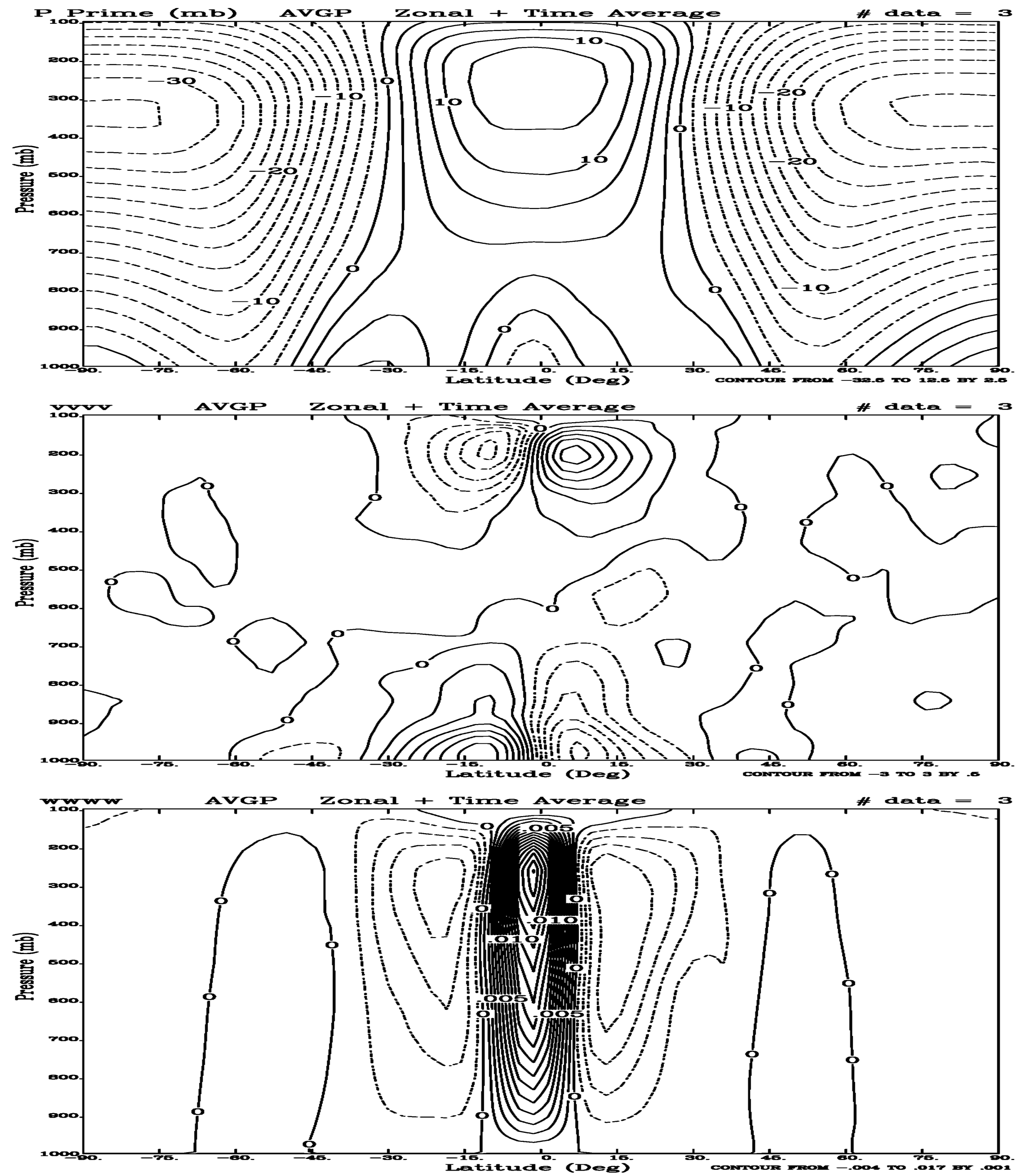




perturbation pressure

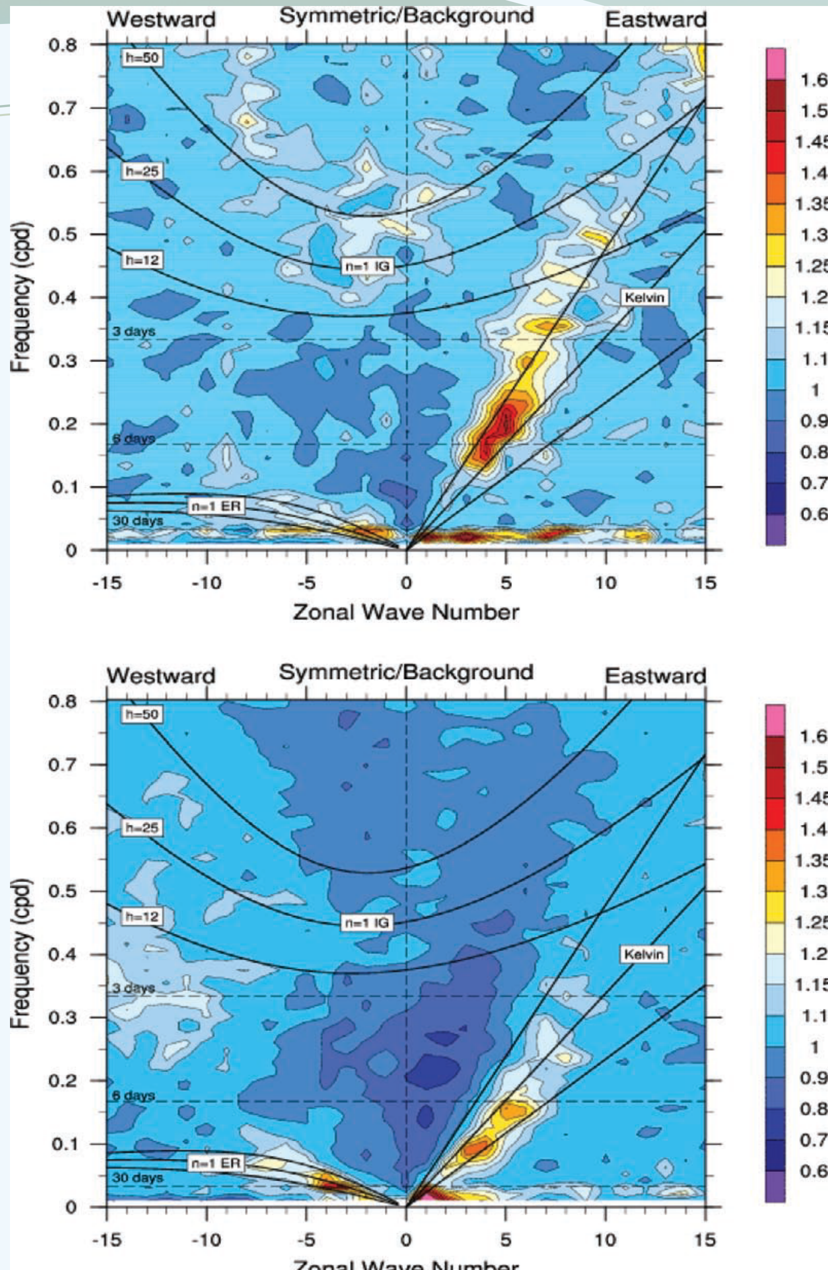
meridional wind

vertical velocity



Final remarks and outlook

- A Nonhydrostatic Icosahedral Model (NIM) dycore has been developed and tested w/ mesoscale benchmarks
- Implemented NIM on CPU/GPU for efficient model integration.
- Incorporated GFS and GRIMs physical packages into NIM dycore.
- Aqua-planet simulations to test dynamics/physics interfaces.
- Equatorial waves analysis, CPs, Super-Parameterization, and GCRMs.



Hurrell, etal. BAMS, 2009

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•NIM for high resolution real time weather forecasts initialized w/ GSI.