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

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**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 simulations.
- 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.
Novel features of FIM/NIM:

- Finite-volume Integrations on *Local Coordinate*
- Conservative and Monotonic Adams-Bashforth 3rd-order FCT Scheme
- FIM: Hybrid $\sigma$-$\theta$ Coordinate w/ GFS Physics

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- **Efficient Indirect Addressing Scheme on Irregular Grid**
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- **Grid Optimization for Efficiency and Accuracy**
Comparisons of Icosa-grids

<table>
<thead>
<tr>
<th></th>
<th>Uniformity</th>
<th>Regularity</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SBiR</strong></td>
<td>1.195</td>
<td>1.476</td>
</tr>
<tr>
<td><strong>MBiR</strong></td>
<td>1.175</td>
<td>1.405</td>
</tr>
<tr>
<td><strong>SGCL</strong></td>
<td>1.476</td>
<td>1.194</td>
</tr>
<tr>
<td><strong>MGCL</strong></td>
<td>1.446</td>
<td>1.135</td>
</tr>
</tbody>
</table>
Williamson et al. (1992) Case V: Zonal flow over Mountain (no dissipation)
SBiR (G8/dt=45 sec)

EXPER FIM-8 03/22/2009 (00:00) 120 hr fcst
Valid 03/27/2009 00:00 UTC
Precipitable Water (mm), 500 mb hgt (m)
MGCL (G8/dt=36 sec, blow up with dt=45)
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- Novel Features of NIM:
  - Three-dimensional finite-volume integration.
  - Conservative flux formulation on height coordinate.
Flux form GEs on 3-D control volume on height coord.

\[
\begin{align*}
\frac{\partial U}{\partial t} + \frac{\partial (Uu)}{\partial x} + \frac{\partial (Vu)}{\partial y} + \frac{\partial (Wu)}{\partial z} + \gamma R \pi \frac{\partial \Theta'}{\partial x} & = F_u \\
\frac{\partial V}{\partial t} + \frac{\partial (Uv)}{\partial x} + \frac{\partial (Vv)}{\partial y} + \frac{\partial (Wv)}{\partial z} + \gamma R \pi \frac{\partial \Theta'}{\partial y} & = F_v \\
\frac{\partial W}{\partial t} + \frac{\partial (Uw)}{\partial x} + \frac{\partial (Vw)}{\partial y} + \frac{\partial (Ww)}{\partial z} + \left( \gamma R \pi \frac{\partial \Theta'}{\partial z} - \bar{\rho} g \frac{\pi'}{\pi} + \rho' g \right) & = 0 \\
\frac{\partial \rho}{\partial t} + \frac{\partial (U)}{\partial x} + \frac{\partial (V)}{\partial y} + \frac{\partial (W)}{\partial z} & = 0.
\end{align*}
\]

\[
\begin{align*}
\frac{\partial \Theta}{\partial t} + \frac{\partial (U \Theta)}{\partial x} + \frac{\partial (V \Theta)}{\partial y} + \frac{\partial (W \Theta)}{\partial z} & = \Theta \dot{H} \\
\frac{\partial (\rho q)}{\partial t} + \frac{\partial (U q)}{\partial x} + \frac{\partial (V q)}{\partial y} + \frac{\partial (W q)}{\partial z} & = S_q
\end{align*}
\]

\[
(U, V, W, \Theta, \rho) = (\rho u, \rho v, \rho w, \rho \Theta, \rho); \quad \Theta(x, y, z, t) = \bar{\Theta}(z) + \Theta'(x, y, z, t)
\]

\[
\rho(x, y, z, t) = \bar{\rho}(z) + \rho'(x, y, z, t); \quad \nabla p = \gamma R \pi \nabla \Theta
\]

\[
p = p_0 \left( \frac{R \Theta}{p_0} \right)^\gamma; \quad \pi = \left( \frac{p}{p_0} \right)^\kappa
\]
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Novel Features of NIM:

- Three-dimensional finite-volume integration.
- Conservative flux formulation on z-coordinate.
- 3-D volume Integration to calculate PGF.
Various PGF treatments over topography

\[ \frac{\partial p}{\partial x} \sim \frac{\partial p}{\partial x'} - z_z \frac{\partial p}{\partial z'} \]

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.

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**Novel Features of NIM:**

- Three-dimensional finite-volume integration.
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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

Test Case 21
Mountain Wave - Vertical Velocity (m/s) - 7200 s

MPAS/G5

NIM/G5

w (m/s) after 60 min
Endgame

DCMIP: 2.2 (small earth)

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
## NIM 800-day aqua-planet simulation

| MODEL   | NIM/GFS  
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>SST</td>
<td>Zonally uniform, max. temp. on equator</td>
</tr>
<tr>
<td>Resolution</td>
<td>G5 ($\Delta x \sim 240$ km)</td>
</tr>
<tr>
<td>Vertical</td>
<td>32 Stretch layers</td>
</tr>
<tr>
<td>Model top</td>
<td>25 km</td>
</tr>
<tr>
<td>$\Delta t$</td>
<td>20 min</td>
</tr>
</tbody>
</table>
Hoskins et al. (1999), Tellus

NIM aqua-planet simulation

NIM mean zonal wind
**T Tendency from physics \((K/6\text{hr})\)**

**G6K32**

**G6K96**
NIM real data simulation initialized with GFS initial condition
(comparisons of precipitation 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
DAY 5

NASA GPCP V1DD
1-degree daily combination precip estimates

FIM G06
2007-07-17 00:00:00 120hr fcst / 24hr accum precip

NIM G06
2007-07-17 00:00:00 120hr fcst / 24hr accum precip

min= 0.00 max=224.35 mm/day
min= 0.00 max=176.95 mm/day
NIM/GPU implementation (fine grain parallelization)
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

<table>
<thead>
<tr>
<th></th>
<th>6-core Westmere CPU</th>
<th>8-core Opteron CPU</th>
<th>8-core Sandybridge CPU</th>
<th>C2050 Fermi GPU</th>
<th>K20X Kepler GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time Period</td>
<td>86.8</td>
<td>143.0</td>
<td>60.3</td>
<td>25.1</td>
<td>20.7</td>
</tr>
</tbody>
</table>

- 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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