Design and Testing of
A Global Cloud Resolving Model
Acknowledgments

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Landscape

Regional non-hydrostatic dynamical core → CRM → MMF → GCM → Cloud-Scale Physics

Cyclone-Scale Physics

Global non-hydrostatic dynamical core

GCRM
GCRM Design Elements

- Governing equations
- Unified system
- Vector vorticity equation
- Geodesic grid
- Parameterizations
WHY DO WE WANT TO FILTER SOUND WAVES?

There is no evidence for the meteorological importance of sound waves.

**Non-filtered system:**
- Sound waves are generated.
- Models try to *numerically stabilize* those waves.
  (e.g., splitting technique, Klemp and Wilhelmson 1978).

**Filtered system:**
- Sound waves are *filtered at their origin* without depending on numerical stabilization.
- Modeling can concentrate on simulating motions of interest.

Smith and Bannon (2009) showed that filtered models can be more economical
than non-filtered models with almost identical results.
FILTERING SOUND WAVES

There are two ways to filter sound waves.

Quasi-hydrostatic system:

\[
\frac{Dw}{Dt} + \frac{1}{\rho} \frac{\partial p}{\partial z} = -g
\]

Vertical momentum equation becomes diagnostic.

To satisfy this for all \( t \), vertical velocity must be passive to other variables.

Anelastic system:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0
\]

Continuity equation becomes diagnostic.

To satisfy this for all \( t \), pressure gradient force must be passive to other forces.

For cloud-resolving models, filtering must be this type.
The horizontally uniform reference state used in the classical anelastic approximation is unacceptable in a global model, even though it may be OK in a regional model.
THE UNIFIED SYSTEM VS. OTHER SYSTEMS

(a) Compressible non-hydrostatic
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0
\]
with no modification of the momentum equation

(b) Quasi-hydrostatic
\[
\frac{\partial \rho_{qs}}{\partial t} + \nabla \cdot (\rho_{qs} \mathbf{V}) = 0
\]
with the hydrostatic equation

(c) Anelastic non-hydrostatic
\[
\nabla \cdot (\rho_0 \mathbf{V}) = 0
\]
with an approximated vertical momentum equation

(d) Unified
\[
\frac{\partial \rho_{qs}}{\partial t} + \nabla \cdot (\rho_{qs} \mathbf{V}) = 0
\]
with no modification of the momentum equation

The unified system is a generalization of both the quasi-hydrostatic and anelastic systems.
(important in code development and evaluation)
DISPERSION RELATION FOR PERTURBATIONS ON A RESTING ISOTHERMAL ATMOSPHERE ON A β-PLANE (WITH QUASI-GEOSTROPHIC APPROXIMATION)

Anelastic

Pseudo-Incompressible

Compressible Non-Hydrostatic, Unified & Quasi-Hydrostatic
Unified System: Summary

- Fully compressible for hydrostatic motion, and anelastic for non-hydrostatic motion
- No reference state
- Filters vertically propagating sound waves
- Permits the Lamb wave
- Much more accurate than the anelastic system
  - Global applicability
  - Large static stability, e.g., stratosphere
  - Phase speeds of long Rossby waves
- Conserves mass and total energy
Vorticity across scales
Why use the vector vorticity equation?

- The pressure-gradient force is one of the major terms in the momentum equation.

- It plays only a passive role in the anelastic system, often counteracting other forces (e.g., the “virtual mass” effect).

- Therefore, the net effects of forces can be represented more simply if the pressure-gradient force is eliminated.

- This leads to the vector vorticity equation.

- Almost all weather systems are dominated by vorticity.

- A reasonable discretization of the 3D momentum equation does not necessarily correspond to a reasonable discretization of the 3D vorticity equation.
Geodesic Grid

Icosahedron

Bisect each edge and connect the dots

Pop out onto the unit sphere

And so on, until we reach our target resolution...
## Some grids of interest

<table>
<thead>
<tr>
<th>Level of recursion</th>
<th>Number of grid columns</th>
<th>Distance between grid columns, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>41,943,042</td>
<td>3.909</td>
</tr>
<tr>
<td>12</td>
<td>167,772,162</td>
<td>1.955</td>
</tr>
<tr>
<td>13</td>
<td>671,088,642</td>
<td>0.977</td>
</tr>
<tr>
<td>Red Team GCRM</td>
<td>Blue Team GCRM</td>
<td></td>
</tr>
<tr>
<td>---------------------------------------------------</td>
<td>-----------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Unified System</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Geodesic grid</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Charney-Phillips vertical staggering</td>
<td>Same</td>
<td></td>
</tr>
<tr>
<td>Multigrid Solver</td>
<td>Same (but used differently)</td>
<td></td>
</tr>
<tr>
<td>Predict vertical component of vorticity, and divergence of horizontal wind</td>
<td>Predict horizontal vorticity vector</td>
<td></td>
</tr>
<tr>
<td>Z grid horizontal staggering</td>
<td>C grid horizontal staggering</td>
<td></td>
</tr>
<tr>
<td>No computational modes</td>
<td>Computational mode in wind (filtered in tendency terms)</td>
<td></td>
</tr>
</tbody>
</table>
Jung and Arakawa (2008) demonstrated the “vector vorticity model” (VM) on a quadrilateral grid with the anelastic approximation, using Lorenz vertical staggering.

Celal Konor has now completed and tested the dynamics of version of the VVM that runs on a plane of perfect hexagons, with Charney-Phillips vertical staggering, still using the anelastic approximation. We call this model the “Hex VVM.”

Physics is being installed in the model now.

The Hex-VVM has been used as a testbed, to find and solve problems that might arise in the Blue-Team GCRM.

[Diagram showing the progression from Cartesian VVM to Hex VVM to Anelastic Geodesic VVM to Unified Geodesic VVM]
\( \eta = 0 \) at the upper boundary.
\( \zeta_T \) is predicted for the top layer.
The boundary condition \( w = 0 \) determines \( \delta_T \).
\( \mathbf{v}_n \) is determined from the streamfunction and velocity potential.

\( \eta \) is predicted at interior interfaces.
\( \zeta \) is diagnosed from \( \zeta_T \) and \( \eta \).
\( w \) is obtained from a 3D elliptic equation.
\( \mathbf{v}_n \) is determined from \( \eta \) and \( w \).
\( \theta \) is predicted at every interface.

\( \eta = 0 \) at the lower boundary (frictionless case).
Lower boundary condition is \( w = 0 \).
Steps along the way

- **3D-elliptic solver.** Solve for vertical velocity $w$ using $\eta$.

- **Advection of $\eta$.** Predict the horizontal component of vorticity $\eta$.

- **Advection of $\zeta_T$ defined at cell corners.** Predict the vertical component of vorticity $\zeta_T$ in the top layer.

- **2D-elliptic solver defined at cell corners.** Diagnose horizontal wind $v_T$ in the top layer using $\zeta_T$ and $\delta_T$.

- **Advection of $\theta$ defined at cell centers.** Predict potential temperature $\theta$. 

A simple test of the 3D multigrid solver

- Prescribed analytic potential temperature perturbation
  \[ B = g \frac{\theta'}{\theta_0} (= 300 K) \]

- Implied tendency in the horizontal vorticity equation
  \[ \eta = -\Delta t \mathbf{k} \times \nabla_H B \]

- Taking the curl forms the right-hand-side of the \( w \) equation.
  \[ \nabla^2 w + \frac{\partial}{\partial z} \left[ \frac{1}{\rho} \frac{\partial}{\partial z} (\rho w) \right] = -\mathbf{k} \cdot \nabla_H \times \eta \]
Scaling test of 3D-multigrid on Jaguar

- The **NCCS Cray XT5** with 181,00 cores
- 20 V-cycles
- 80 layers

<table>
<thead>
<tr>
<th>Grid resolution</th>
<th>Time (s)</th>
<th>Number of cores</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5120</td>
<td>10240</td>
</tr>
<tr>
<td>41,943,042</td>
<td>8.652</td>
<td>4.535</td>
</tr>
<tr>
<td>(11) (3.909km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>167,772,162</td>
<td>35.567</td>
<td>18.071</td>
</tr>
<tr>
<td>(12) (1.955km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>671,088,642</td>
<td>insufficient memory</td>
<td>79.85</td>
</tr>
<tr>
<td>(13) (0.977km)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Ongoing work with The Blue Team GCRM

- Stretching and tilting terms
- Diagnosis of wind at the model top
- Treatment of the computational mode
This has all been completed and tested by Hiroaki Miura.

He is now adding the SAM physics (with RRTM) to the Unified Geodesic version.
Faster propagation of a cyclone and smaller potential temperature advection in anelastic than in unified.
## Computing speed

<table>
<thead>
<tr>
<th>Grid</th>
<th>PEs (Nodes)</th>
<th>GFlop/sec (performance)</th>
<th>Time (sec/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>40 (10)</td>
<td>5.62568 (6.1 %)</td>
<td>35.0308</td>
</tr>
<tr>
<td>6</td>
<td>160 (40)</td>
<td>18.1987 (4.9 %)</td>
<td>84.9001</td>
</tr>
<tr>
<td>7</td>
<td>640 (160)</td>
<td>63.8086 (4.3 %)</td>
<td>190.9769</td>
</tr>
<tr>
<td>8</td>
<td>2560 (640)</td>
<td>171.023 (2.9 %)</td>
<td>566.8823</td>
</tr>
<tr>
<td>9</td>
<td>2560 (640)</td>
<td>351.833 (6.0 %)</td>
<td>2287.4747</td>
</tr>
<tr>
<td>10</td>
<td>5120 (1280)</td>
<td>696.341 (5.9 %)</td>
<td>*9225.4175</td>
</tr>
<tr>
<td>11</td>
<td>10240 (2560)</td>
<td>1406.80 (6.0 %)</td>
<td>*37090.7180</td>
</tr>
</tbody>
</table>

*Estimates from a 12-hours simulation

Performance is a rate against 9.2 GFlop/sec * nodes

over 1 TFlop/sec
Conclusions

• We currently have a working non-hydrostatic geodesic dynamical core of unique design.

• Off-the-shelf “local” physics is being added to the model now.

• A second non-hydrostatic geodesic dynamical core is nearing completion.
Landscape

Regional non-hydrostatic dynamical core

Cyclone-Scale Physics

CRM

Cloud-Scale Physics

GCRM

MMF

GCM

Global non-hydrostatic dynamical core