Progress with the GCRM(s)

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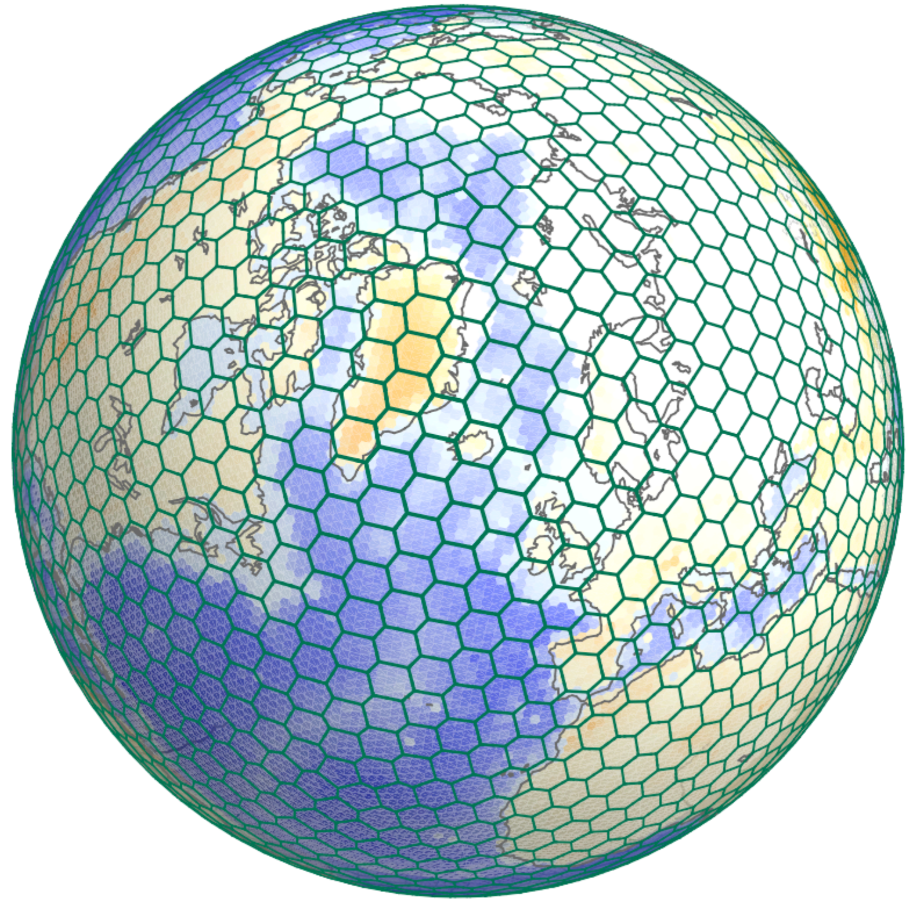
Goals

- Uniform global horizontal grid spacing of 4 km or better ("cloud permitting")
- 100 or more layers up to at least the stratopause
- Parameterizations of microphysics, turbulence (including small clouds), and radiation
- Execution speed of at least several simulated days per wall-clock day on immediately available systems

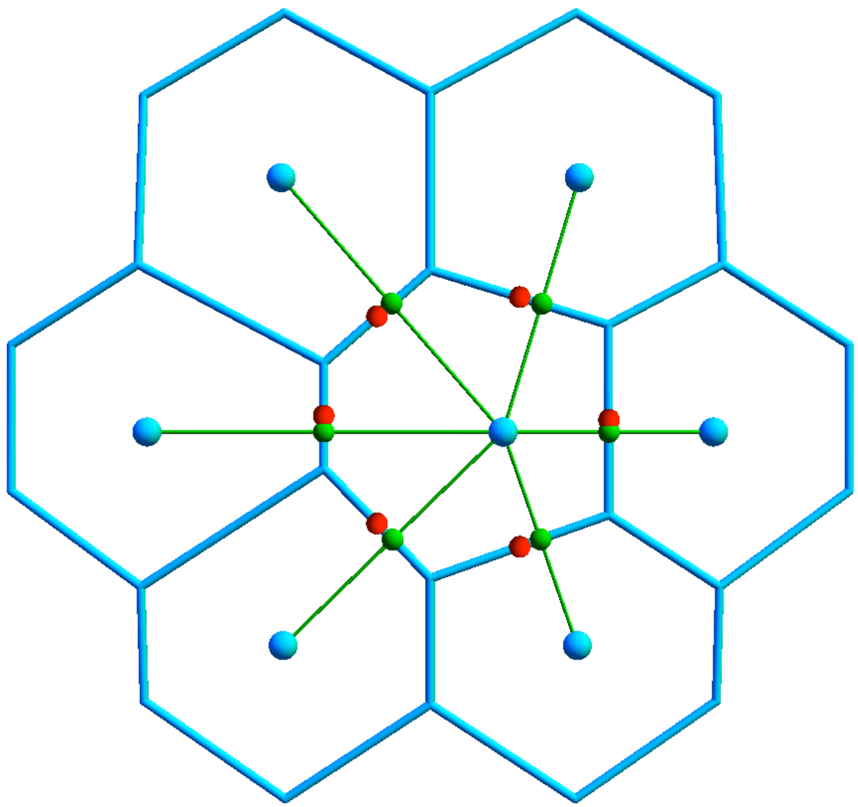
Icosahedral grid

- This grid provides approximately homogeneous and isotropic resolution over the sphere.
- There are 12 pentagons and N-12 hexagonal cells.
- Resolution as a function of cells:

(N) number of cells	global grid point spacing (km)
(6) 40,962	125.1
(7) 163,342	62.55
(8) 655,362	31.27
(9) 2,621,442	15.64
(10) 10,485,762	7.819
(11) 41,943,042	3.909



Ross “tweaks” the grid to improve accuracy



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.

The horizontally uniform reference state used in the anelastic approximation is unacceptable in a global model, even though it may be OK in a regional cloud 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

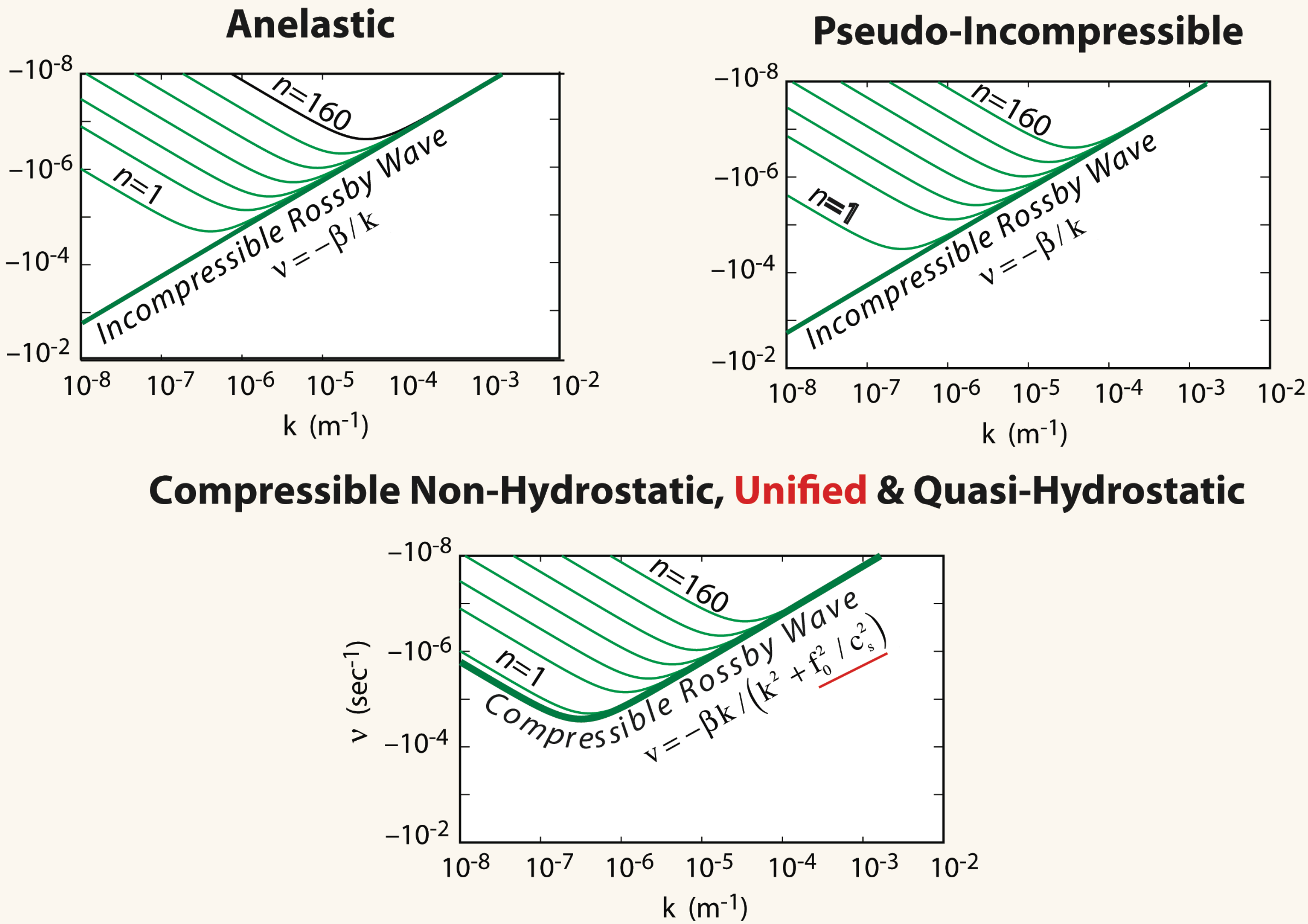
The unified system is a generalization of both the quasi-hydrostatic and anelastic systems.

(important in code development and evaluation)

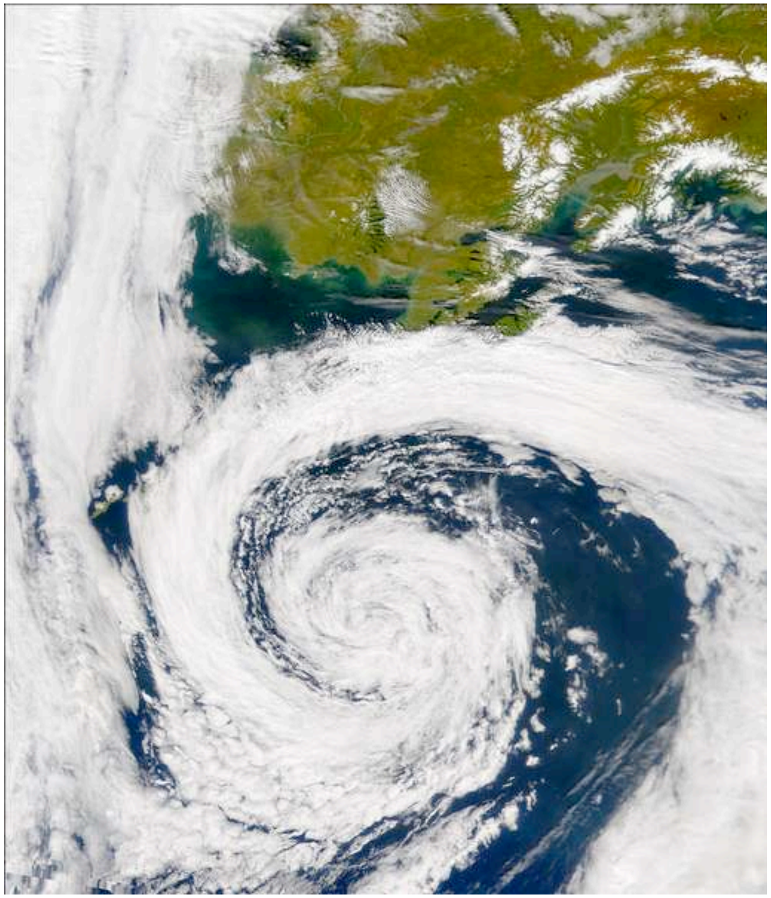
DISPERSION RELATION FOR PERTURBATIONS

ON A RESTING ISOTHERMAL ATMOSPHERE ON A β-PLANE

(WITH QUASI-GEOSTROPHIC APPROXIMATION)



Vorticity across scales



WHY DO WE WANT TO USE THE VECTOR VORTICITY EQUATION ?

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

Yet it plays only a passive role in the anelastic system, often counteracting other forces (“virtual mass” effect.)

Thus the net effect of the forces can be more directly represented if the pressure gradient force is eliminated.

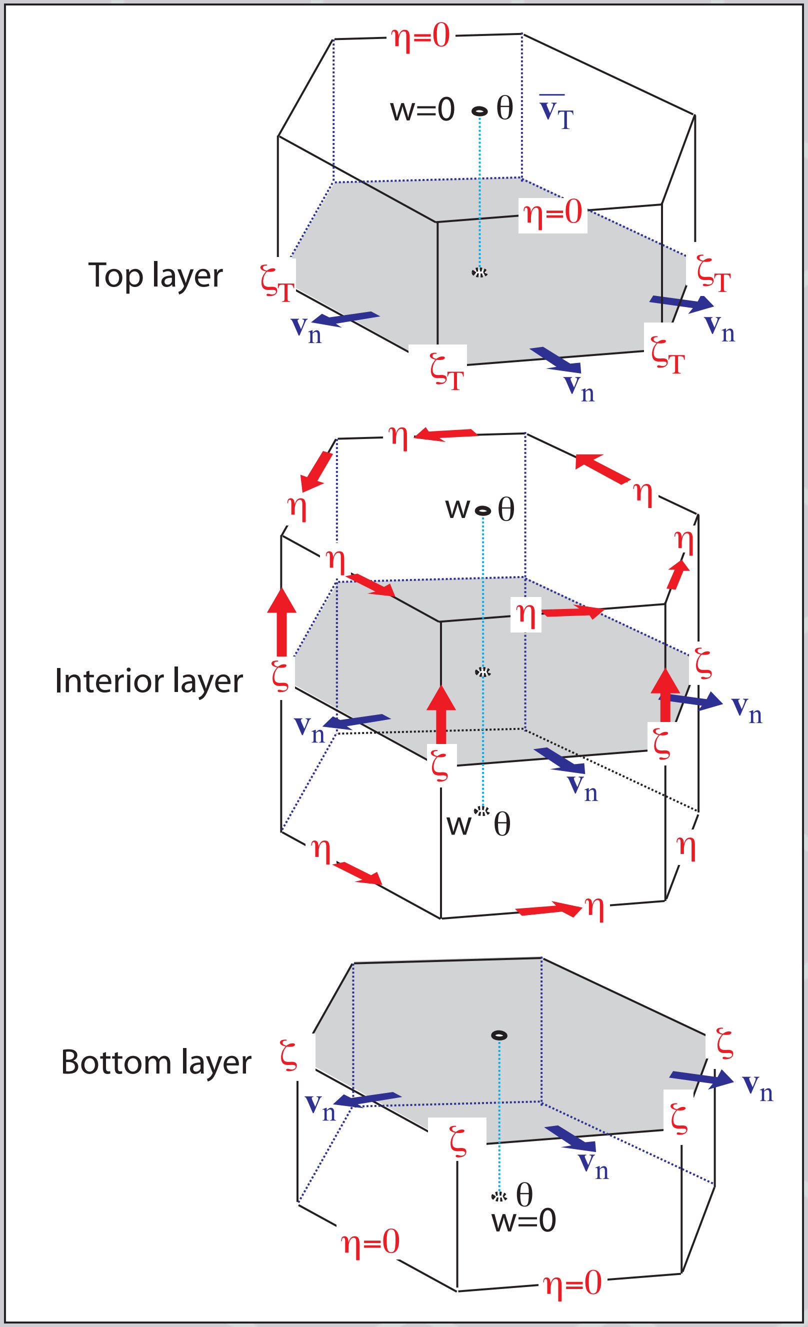
The result of elimination is the 3D vector vorticity equation, which predicts $\nabla \times \mathbf{V}$ *.*

Development of a Vector-Vorticity Dynamical Core on a Regular Hexagonal Grid (Hex-VVDC)

Celal S. Konor and Akio Arakawa

- **The Hex-VVDC is an application of the VVDC of Jung and Arakawa (2008) to a regular hexagonal grid on a planar domain.**
- **The VVDC predicts the horizontal vorticity (η) and diagnoses the vertical vorticity (ζ) from η (using a vertical boundary condition) by requiring that the 3D vorticity be nondivergent.**
- **The current version is based on the non-hydrostatic anelastic system, which can be extended to the Unified System through add-on modules.**
- **The 3D elliptic equation that filters the sound waves determines the vertical velocity.**
- **The Charney-Phillips grid is used in the vertical discretization.**
- **The Hex-VVDC has been used to find and solve problems that might also arise in the GCRM.**

3D Grid



h = 0 at the upper boundary.

g_T is predicted for the top layer.

Upper boundary condition is w = 0.

$\mathbf{v}_n$ is determined from streamfunction and velocity potential. Mean velocity is predicted.

h is predicted at interior interfaces.

g is diagnosed from g_T and h at layers.

w is solved from a 3D elliptic equation.

$\mathbf{v}_n$ is determined from h and w.

i is predicted at every interface.

h = 0 at the lower boundary (frictionless case).

Lower boundary condition is w = 0.

Discretization on Regular Hexagonal Grid (Cont.)

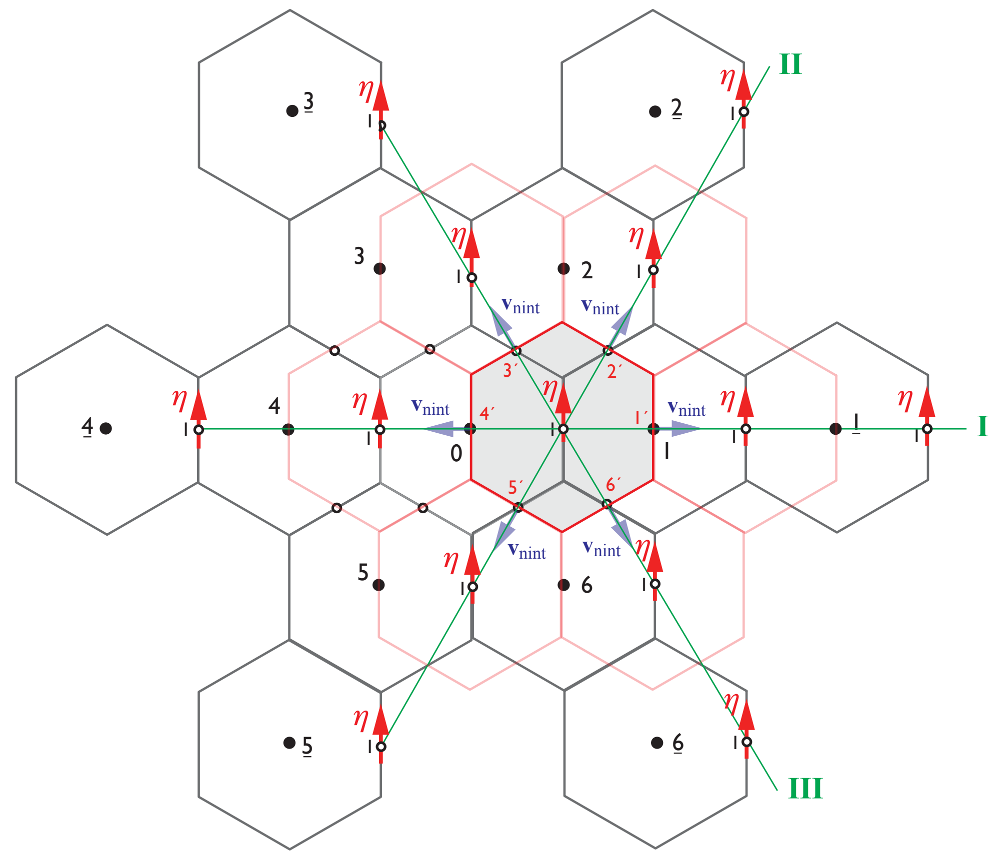
Determination of the flux convergence of h vector for the cell walls is a major discretization challenge.

The challenge appears due to difficulties in, *i*) properly determining a horizontal control volume, *ii*) properly interpolating the velocity to the edges of this control volume, and *iii*) advecting a vector.

Flux convergence of horizontal vorticity

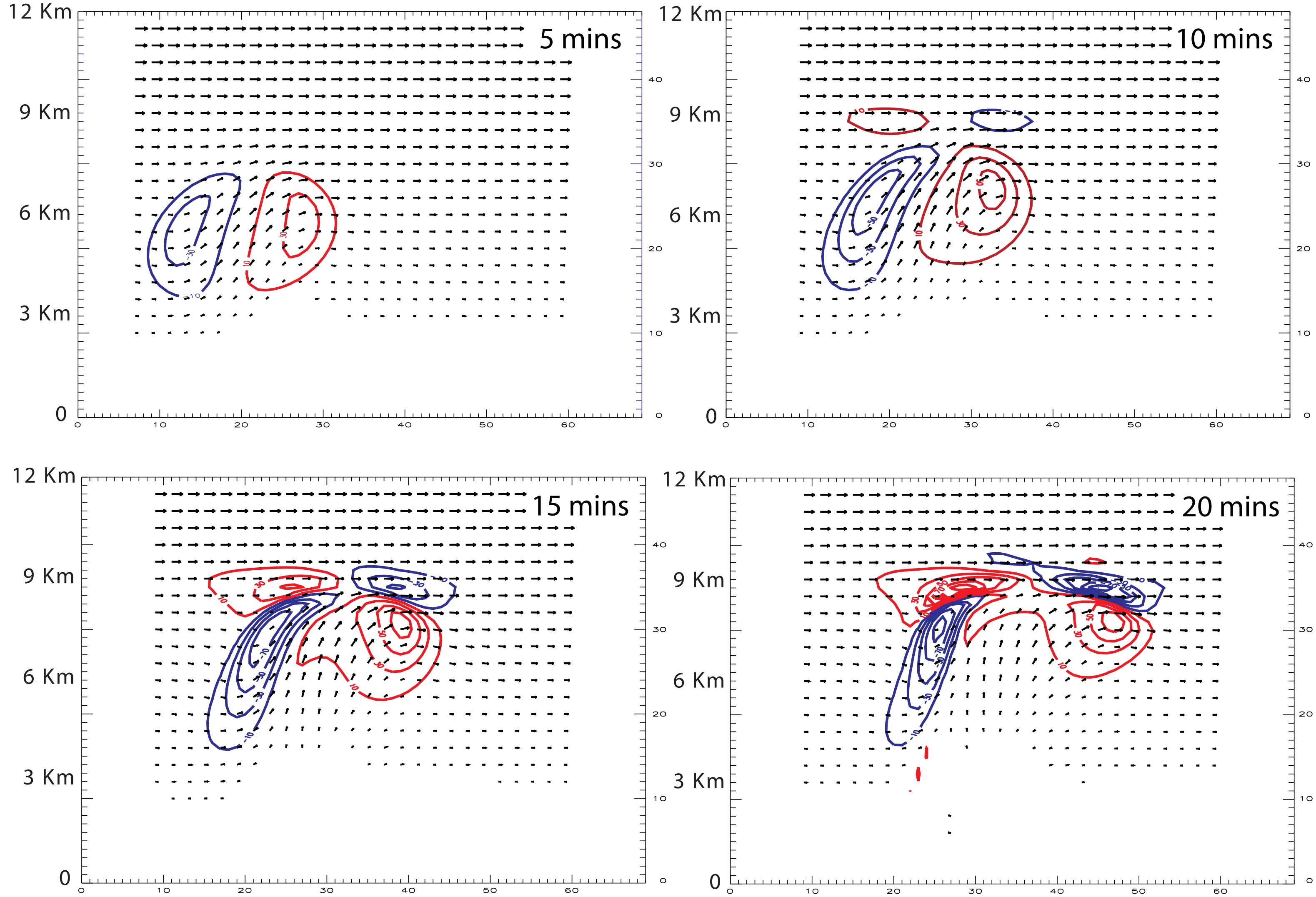
$$\frac{\partial \boldsymbol{\eta}}{\partial t} = -\nabla_H \cdot (\boldsymbol{\eta}\mathbf{v}) - \frac{\partial}{\partial z}(\boldsymbol{\eta} w)$$

Flux Convergence of a vector for the Cell Walls



Ascent of a Buoyant Bubble
With a Sheared Isentropic/Isothermal Basic State

Cross-sections of simulated $\eta - \eta_0$ (10^{-4} s^{-1})



Status and Outlook

- Code development is mostly completed.
- The results are encouraging.
- We will test the full model with physics, including standard test cases from ARM, GCSS, etc.
- We will include the add-on modules needed to use the unified system, and compare the results with the anelastic system.
- We will add topography.

What has been done...

- Many key components of the VVM-sphere have been constructed and tested off-line.
- Now they are ready to be assembled into a model.

The list of components so far...

- ☑ *3D-elliptic solver.* Solve for vertical velocity w using $\boldsymbol{\eta}$.
- ☑ *Advection of $\boldsymbol{\eta}$.* Predict the horizontal component of vorticity $\boldsymbol{\eta}$.
- ☑ *Advection of ζ_T defined at cell corners.*. Predict the vertical component of vorticity ζ_T in the top layer.
- ☑ *2D-elliptic solver defined at cell corners.* Diagnose horizontal wind $\mathbf{v}_T$ in the top layer using ζ_T and δ_T.
- ☑ *Advection of θ defined at cell centers.* Predict potential temperature θ.

A simple test for the 3D multigrid

- Prescribed analytic potential temperature perturbation

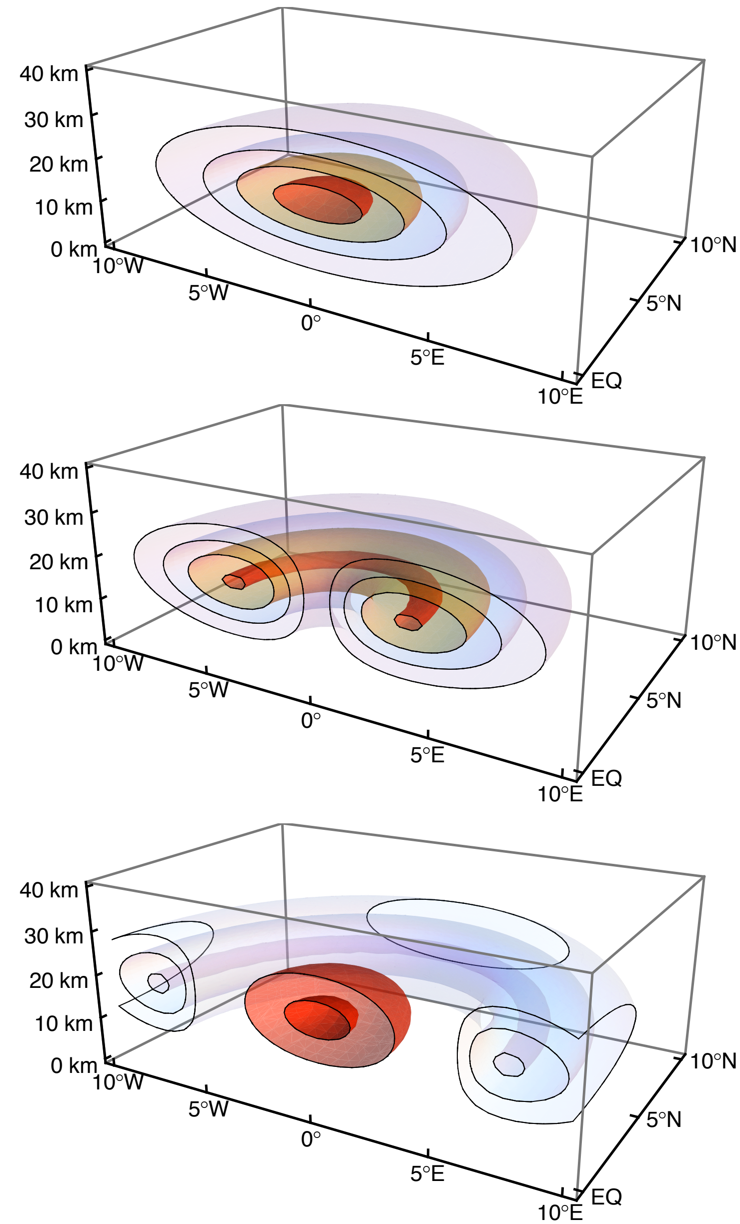
$$B = g\frac{\theta'}{\theta_0(=300K)}$$

- Implied tendency in the horizontal vorticity equation

$$\boldsymbol{\eta} = -\Delta t\,\mathbf{k}\times\nabla_H B$$

- Taking the curl forms the right-hand-side of the w equation.

$$\nabla^2 w + \frac{\partial}{\partial z}\left[\frac{1}{\rho}\frac{\partial}{\partial z}(\rho w)\right] = -\mathbf{k}\cdot\nabla_H\times\boldsymbol{\eta}$$



Convergence of 3D-multigrid

- The following sequence of equations can be used to test convergence of the 3D-multigrid

- Solve for the vertical velocity. The *goodness* of the solution is determined by the number of multigrid cycles.

$$\nabla_H^2 w + \frac{\partial}{\partial z}\left[\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0 w\right)\right] = -\mathbf{k}\bullet\nabla_H \times \boldsymbol{\eta}$$

- Solve for the stream function in the top layer. Set the horizontal velocity in the top layer.

$$\mathbf{v}_T \equiv \mathbf{k} \times \nabla_T \chi_T \quad \text{where} \quad \nabla_H^2 \chi_T = -\left[\frac{1}{\rho_0}\frac{\partial}{\partial z}\left(\rho_0 w\right)\right]$$

- Vertically integrate to get horizontal velocity throughout the remainder of the column.

$$\mathbf{v} \equiv \mathbf{v}_T + \int_{z_T}^{z}\left[\nabla_H w - \mathbf{k} \times \boldsymbol{\eta}\right] dz$$

- With the resulting w and $\mathbf{v}$, the anelastic continuity equation should be zero.

$$\nabla \cdot \left(\rho_0 \mathbf{v}\right) + \frac{\partial}{\partial z}\left(\rho_0 w\right) = 0$$

Convergence of 3D-multigrid

- With 40962 cells and 40 layers

iterations of 3D-multigrid	inf-norm of the continuity equation
2	1.09E-09
4	2.81E-15
8	2.26E-17
20	2.27E-17

Scaling test of 3D-multigrid on Jaguar

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

Time (s)		Number of cores			
		5120	10240	20480	40960
Grid resolution	41,943,042 **(11)** (3.909km)	8.652	4.535	3.071	2.377
Grid resolution	167,772,162 **(12)** (1.955km)	35.567	18.071	8.885	5.646
Grid resolution	671,088,642 **(13)** (0.977km)	insufficient memory	79.85	36.137	18.903

Horizontal component of vorticity

Predict the horizontal component of vorticity $\boldsymbol{\eta}$.

$$\frac{\partial \tilde{\boldsymbol{\eta}}}{\partial t} = -\overbrace{\nabla_H \cdot \left(\tilde{\boldsymbol{\eta}}\mathbf{v}\right)}^{\substack{horizontal\\ advection}} - \overbrace{\frac{\partial}{\partial z}\left(\tilde{\boldsymbol{\eta}} w\right)}^{\substack{vertical\\ advection}} + \overbrace{\tilde{\boldsymbol{\eta}} \cdot \nabla_H \mathbf{v}}^{stretching} + \overbrace{\tilde{\xi}\frac{\partial \mathbf{v}}{\partial z}}^{tilting} + \mathbf{v}\nabla_H \cdot \left(2\boldsymbol{\Omega}_H\right) - \overbrace{\mathbf{k}\times\nabla_H B}^{buoyancy} + \overbrace{\mathbf{k}\times\left(\frac{\partial \mathbf{F}_{\mathbf{v}}}{\partial z} - \nabla_H F_w\right)}^{turbulent-drag\ force}$$

- The **horizontal advection** term is technically complicated. The horizontal component of vorticity is defined at cell edges and requires a *control volume grid defined* at cell edges.
- The remaining terms are less complicated and have been thoroughly described by Celal. Vertical advection, stretching and tilting have been coded but not tested.

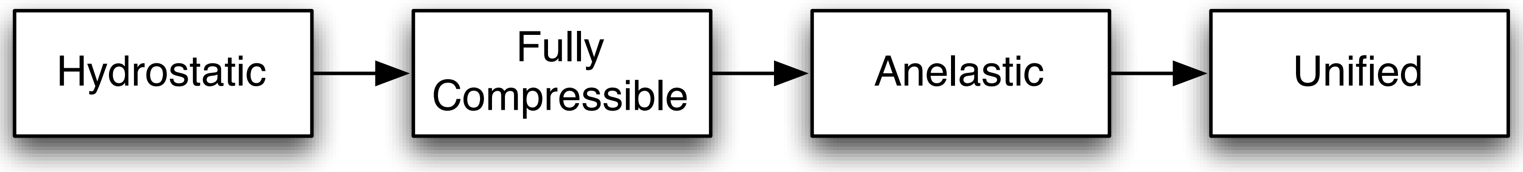
Things to do...

1. Stretching and tilting terms
2. Diagnosis of wind at the model top
3. Treatment of the computational mode

Red Team, Blue Team

- Two GCRM development efforts
  - Create competition
  - Maximize chances of success
  - Compare results
- Shared elements
  - Geodesic grid & multigrid solver
  - Nonhydrostatic dynamics
  - Anelastic system → unified system
  - Charney-Phillips grid
- Differences
  - Blue Team uses VVDC
  - Red Team uses Z-grid (SciDAC 1)

Red Team Strategy

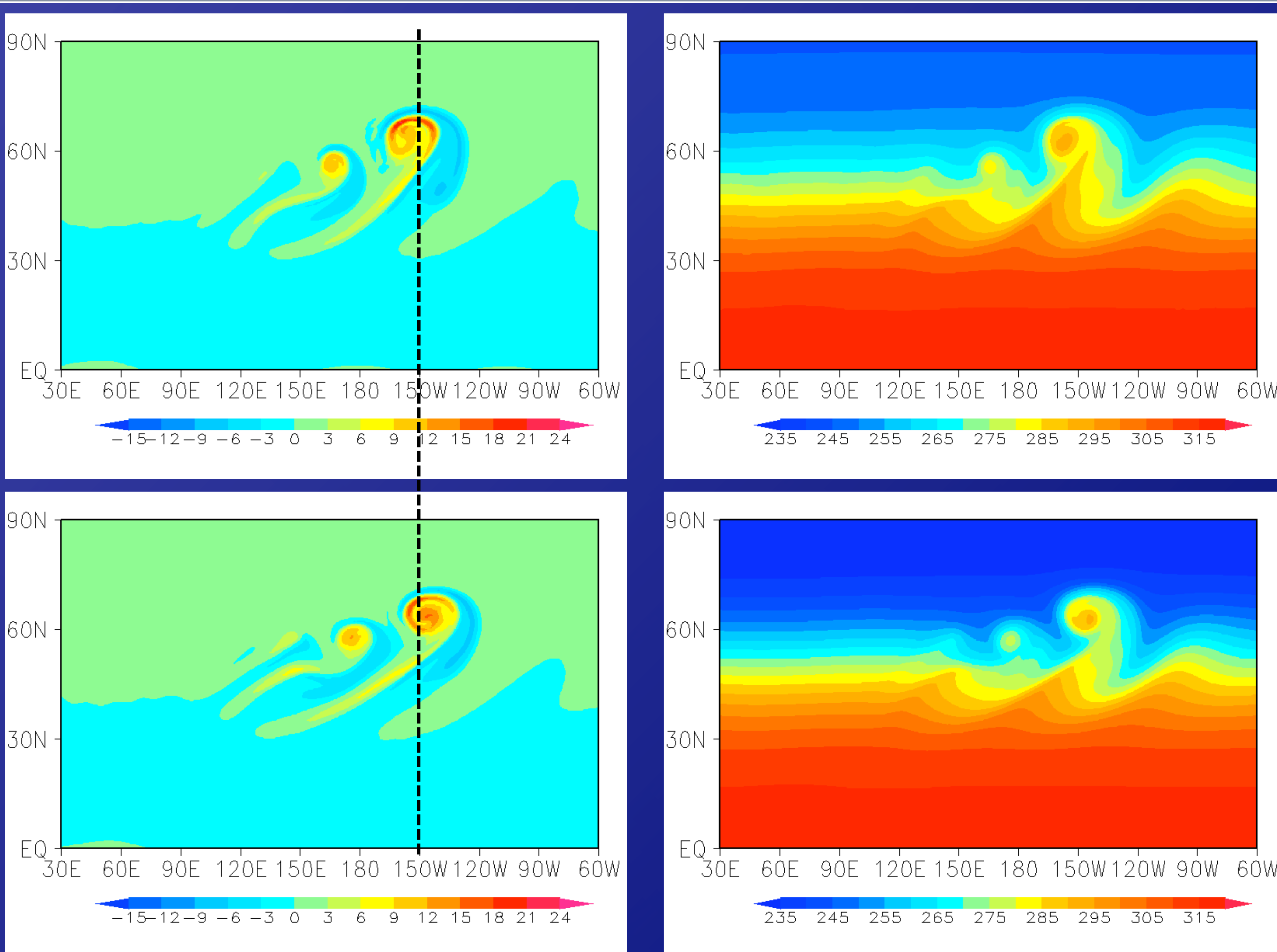


- **All of these steps have been carried out. The last step is still being debugged.**
- **The Red Team model uses the Z-grid.**

Unified vs. Anelastic

Unified

Anelastic



Faster propagation of a cyclone and smaller potential temperature advection in aneastic than in unified.

Computing speed

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

over 1 TFlop/sec

*Estimates from a 12-hours simulation

Performance is a rate against 9.2 GFlop/sec * nodes

Computational challenges

- **Efficient execution on a very large number of processors**
- **Parallel I/O (especially O)**
- **Management and distribution of the voluminous model output**
- **Visualization of the results**

These are "infrastructure" issues that will be faced by anyone using a GCRM.

Summary of Progress

- Unified system
- Hex VVM
- Geodesic VVM
- Z-grid GCRM
- Scaling demonstrations
- I/O API and visualization strategy

The Green Flash

Next Steps

1. Complete Blue-Team GCRM dynamics and test, including Jablonowski test
2. Continue scaling tests out to 80 K processors
3. Modify both GCRMs to use the Unified System, and test
4. Meanwhile, add physics to the Hex-VVM, and test, including ARM and GCSS cases
5. Add physics to both GCRMs, and test
6. Port one or both of the GCRMs to Intrepid
7. Implement topography
8. Perform short-range weather forecasts
9. Quasi-Lagrangian coordinate