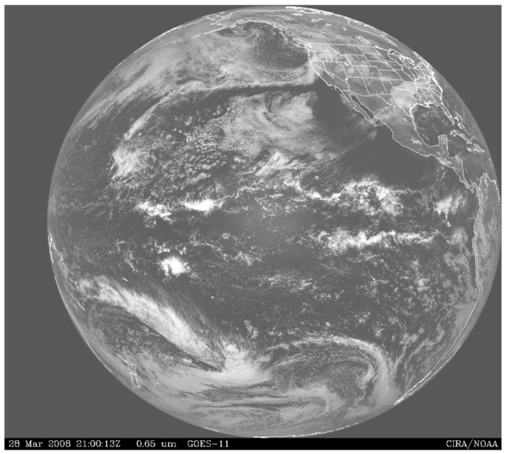
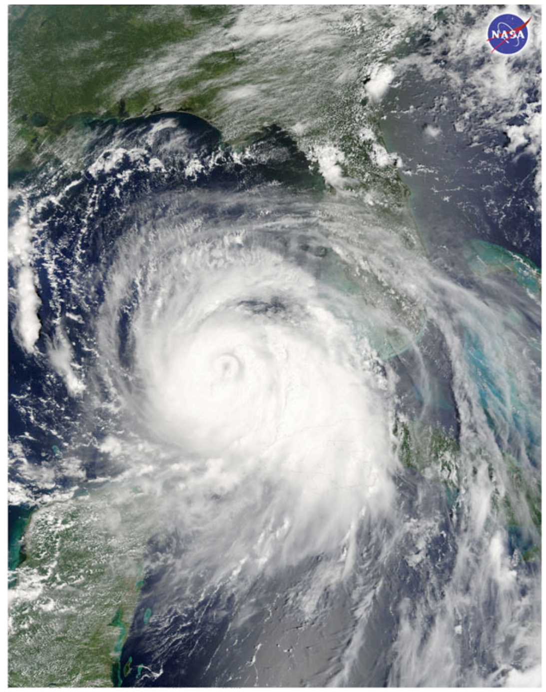
Model for Prediction Across Scales (MPAS)





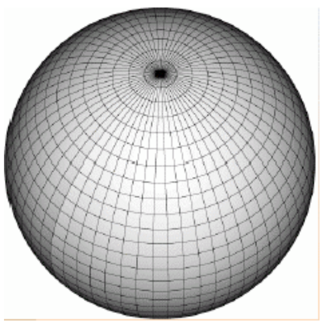
Joe Klemp, Bill Skamarock (NCAR)
Todd Ringler (Los Alamos National Laboratory)
John Thuburn (University of Exeter, UK)

Future Weather/Climate Atmospheric Dynamic Core

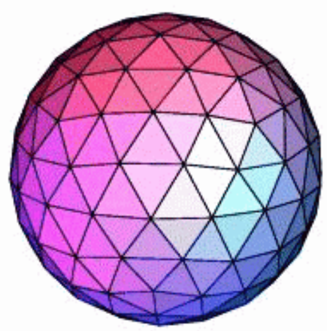
Problems with lat-lon coordinate for global models

- Pole singularities require special filtering
- Polar filters do not scale well on massively parallel computers
- Highly anisotropic grid cells at high latitudes

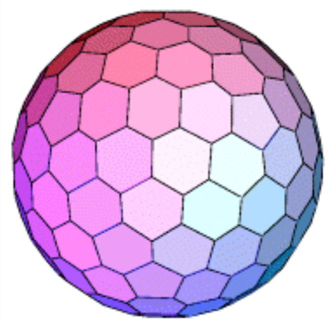
Consideration of alternative spatial discretizations:



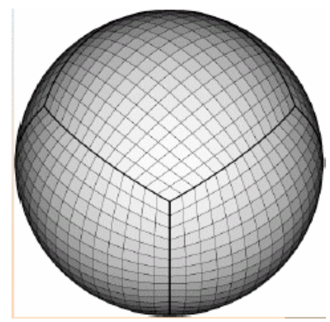
Lat-Lon



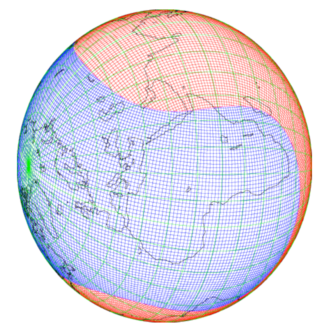
Icosahedral-triangles



Icosahedral-hexagons



Cubed Sphere



Yin-Yang

Priority Requirements:

- Efficient and scales well on massively parallel computers
- Well suited for cloud (nonhydrostatic) to global scales
- Capability for local grid refinement and regional domains
- Conserves at least mass and scalar quantities

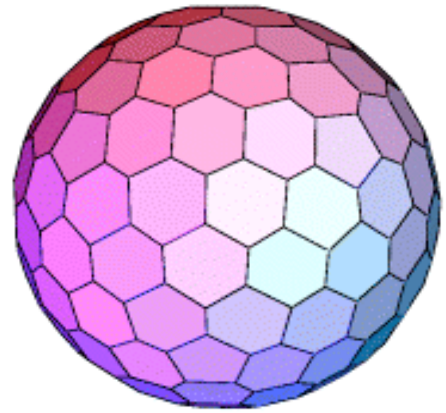
Hexagonal C-Grid

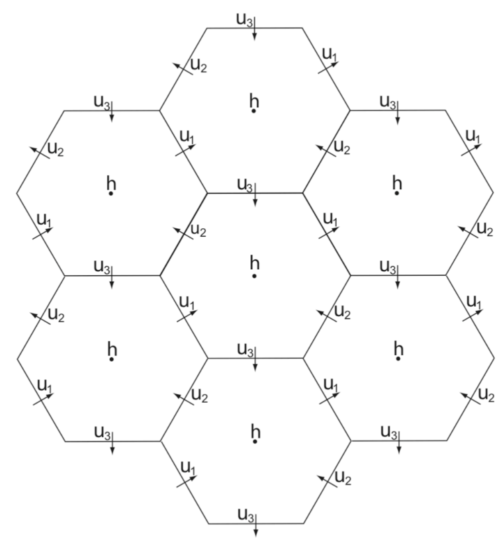
Why a hexagonal grid?

- Removes the pole singularity
- Most isotropic (wave propagation).
- Provides good conservation properties in a finite-volume formulation
- Hexagonal grid permits larger explicit time steps.
- Readily generalized to arbitrarily structured grids

Why a C-grid staggering?

- Provides the highest accuracy for the fast (gravity-wave) modes
- Provides twice the resolution of the A grid, and avoids the parasitic mode





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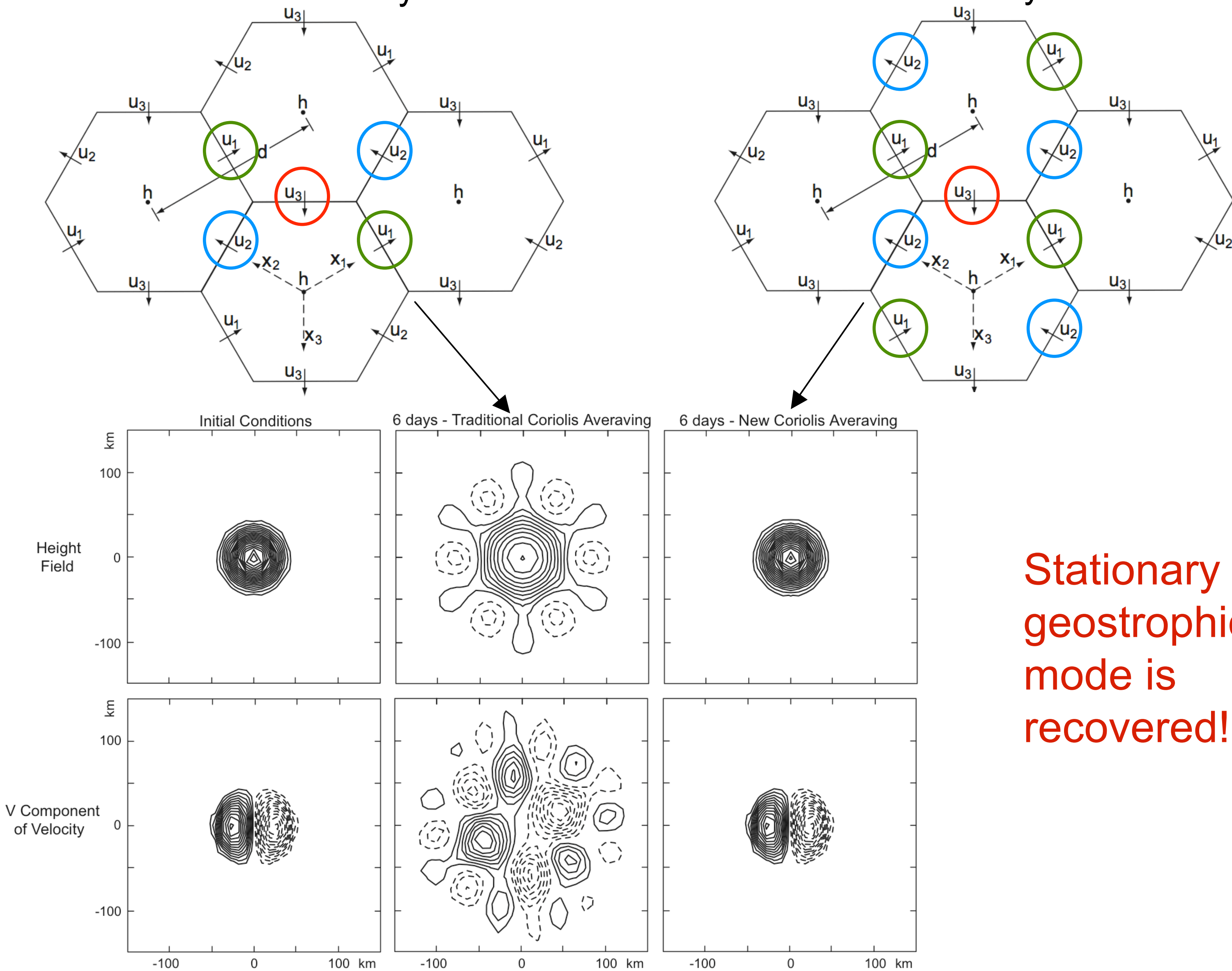
Hexagonal C-Grid Problem: Non-Stationary Geostrophic Mode

Traditional Coriolis velocity construction

New Coriolis velocity construction



Stationary geostrophic mode is recovered!

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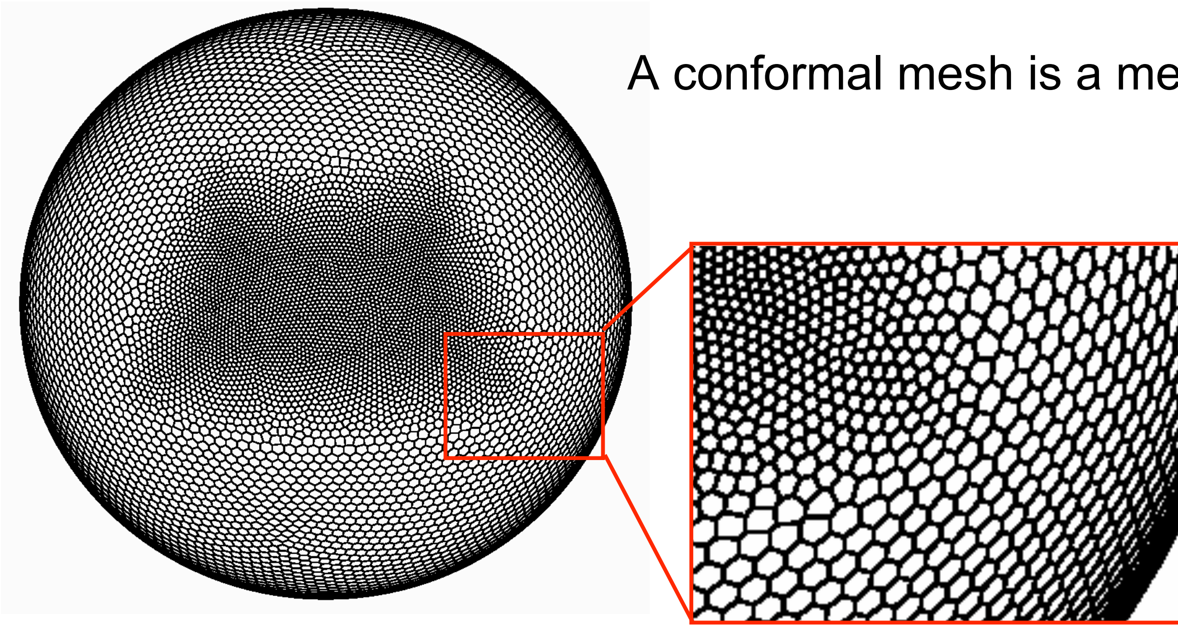
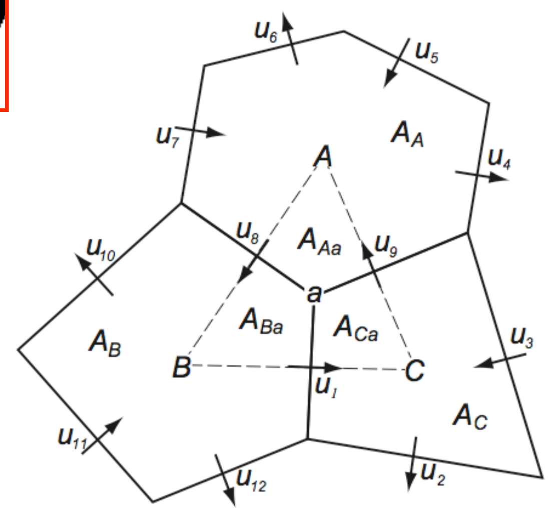
Conformal, Variable-Resolution Meshes



A conformal mesh is a mesh with no hanging nodes.

SCVTs
Spherical Centroidal
Voronoi Tessellations

(Includes Lat/Lon and
conformally-mapped
cubed sphere.)



Cell center is cell center-of-mass

Edges of dual grid intersect edges of primary grid at right angles.

Conjecture: smooth refinement on conformal meshes should mitigate many refinement problems.

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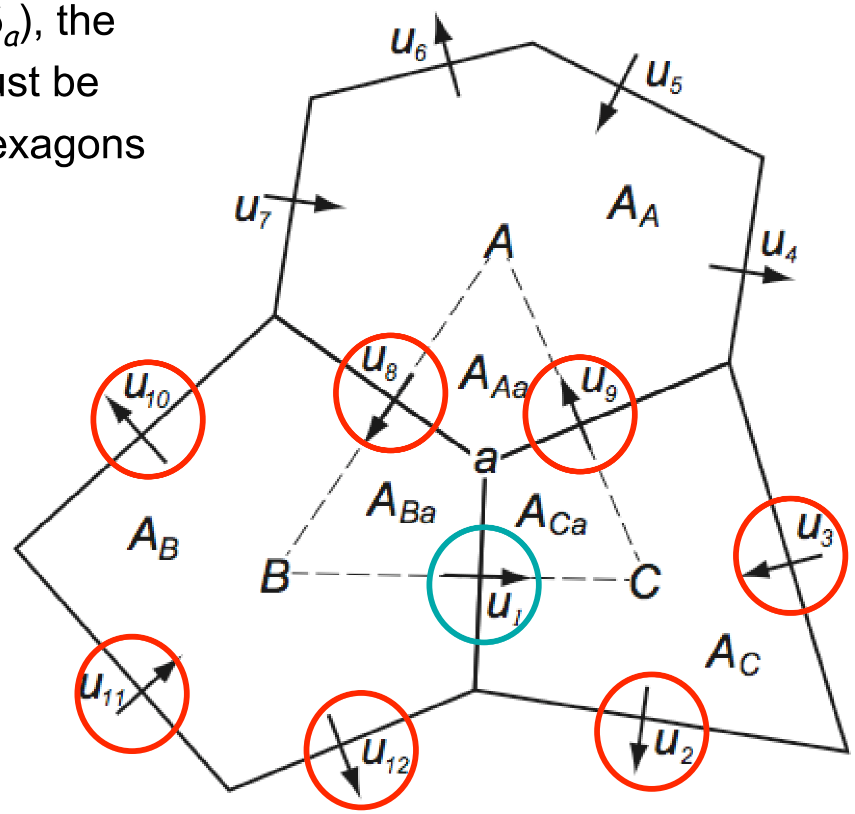
(Michael Duda, MMM)

Generalization for Arbitrarily Structured Grids

In discrete analogue of vorticity equation ($\xi_t = -f\delta_a$), the divergence δ_a on the Delaunay triangulation must be identical to the divergence δ_A on the Voronoi hexagons used in the height equation ($h_t = -H\delta_A$):

$$A_a\delta_a = A_{Aa}\delta_A + A_{Ba}\delta_B + A_{Ca}\delta_C$$



Construct tangential velocities from weighted sum of normal velocities on edges of adjacent grid cells.

$$d_e u_e^{\perp} = \sum_j w_e^j l_j u_j$$

Energy conservation achieved by requiring $w_e^j = -w_j^e$.

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Analytic Results for the Nonlinear Shallow-Water Equations

1. Stationary geostrophic mode is recovered.

2. Potential vorticity is conserved to round-off. PV is compatible with an underlying thickness evolution equation.

3. Total energy is conserved to within time truncation.
   a. Coriolis force is energetically-neutral
   b. Transport of KE is conservative
   c. KE/PE exchange is equal and opposite.

4. It appears that potential enstrophy can be dissipated.

Results hold for a wide class of meshes: Lat/Lon, Voronoi Tessellations, Delaunay Triangulation and Conformally-mapped cubed sphere meshes.

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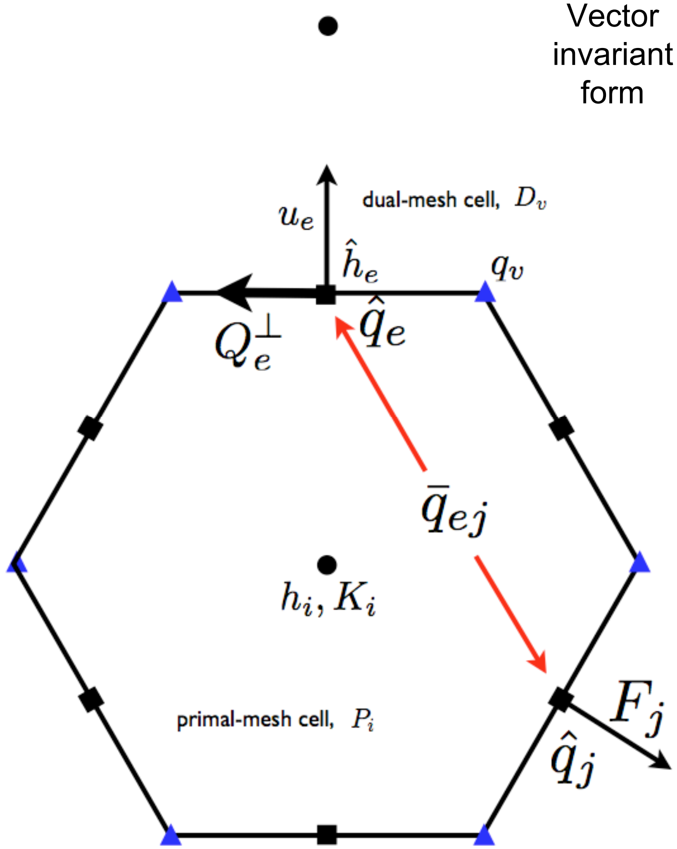
Reconstructing the Nonlinear Coriolis Force

(The nonlinear Coriolis force $Q_e^\perp$ is the PV flux perpendicular to the velocity)



Vector invariant form

$$\frac{\partial u_e}{\partial t} + \widehat{q}_e \, [hu]_e^\perp = [\nabla (gh_i + K_i)]_e$$

$$\frac{\partial u_e}{\partial t} + Q_e^\perp = [\nabla (gh_i + K_i)]_e$$

$$d_e \, Q_e^\perp = \sum_j w_e^j \, l_j \, F_j \, \bar{q}_{ej}$$

$F_j = \hat{h}_j u_j$ thickness flux

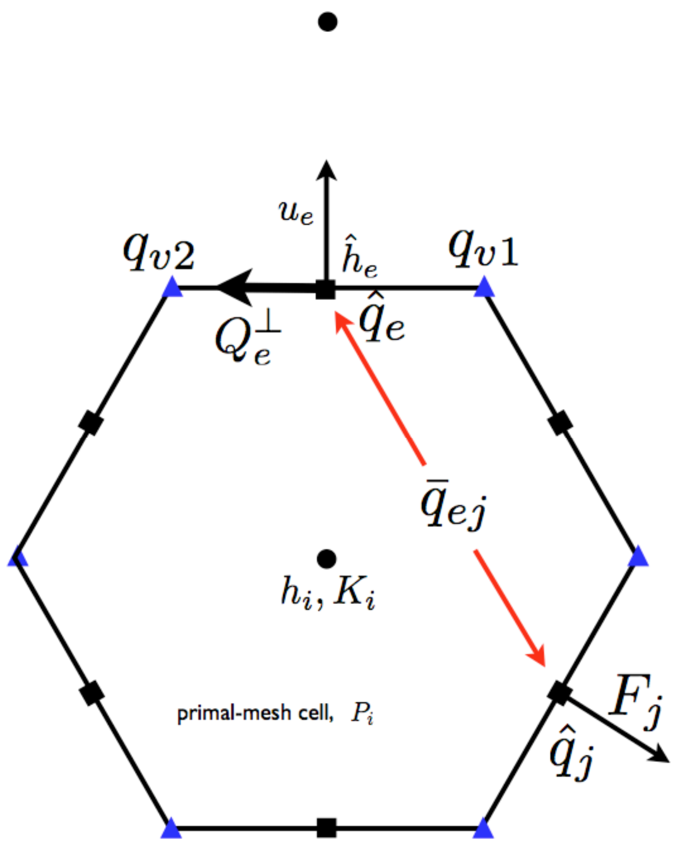
$w_e^j = -w_j^e$ weights are equal and opposite

$\bar{q}_{ej} = \bar{q}_{je}$ PV is symmetric

The nonlinear Coriolis force will be energy neutral for any $\bar{q}_{ej}$

Reconstructing the Nonlinear Coriolis Force

(The nonlinear Coriolis force $Q_e^{\perp}$ is the PV flux perpendicular to the velocity)



$$\frac{\partial u_e}{\partial t} + \widehat{q}_e\,[hu]_e^{\perp} = [\nabla\,(gh_i + K_i)]_e$$

$$\frac{\partial u_e}{\partial t} + Q_e^{\perp} = [\nabla\,(gh_i + K_i)]_e$$

Energy conservation is obtained by:

$$\bar{q}_{ej} = \bar{q}_{je} = \frac{1}{2}\left(\widehat{q}_e + \widehat{q}_j\right)$$

Energy is conserved for any $\widehat{q}_e$ and any $\widehat{q}_j$!

The APVM is obtained by:

$$\widehat{q}_e = \frac{1}{2}\left(q_{v1} + q_{v2}\right) - \frac{dt}{2}\mathbf{u}\cdot\nabla q$$

Upstream bias leads to dissipation of potential enstropy.

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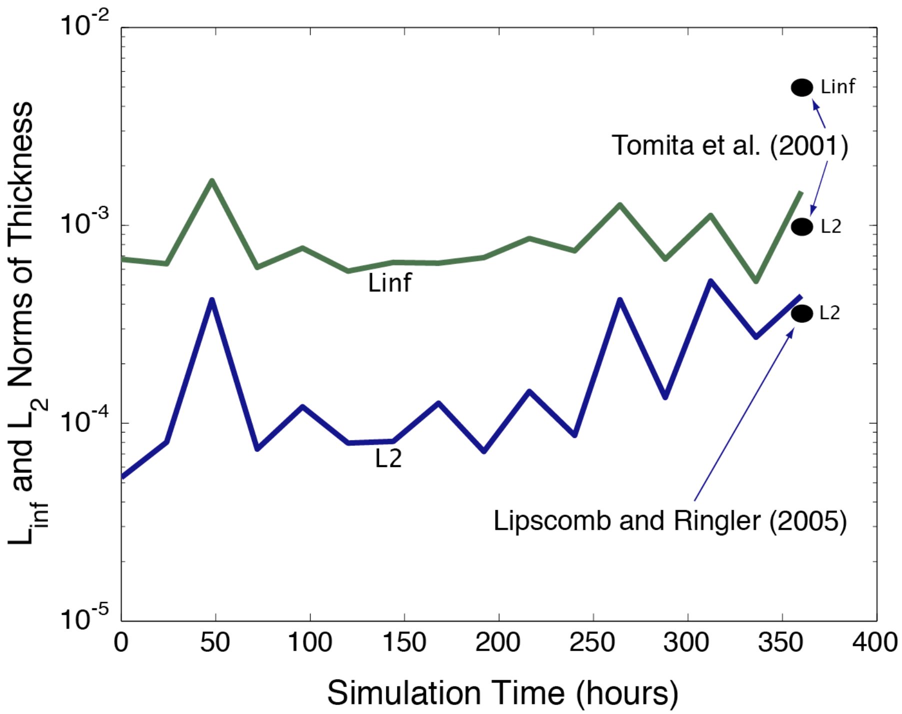
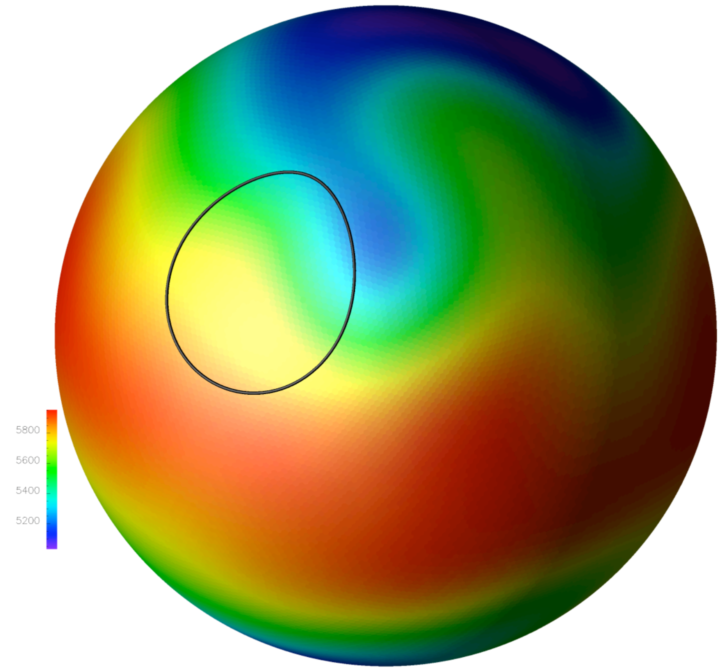
Anticipated Potential Vorticity Method (Sadourny & Basdevant, JAS 1985)

Shallow-Water Test Case 5: Flow over an Isolated Mountain

40962 cells, dx ~ 120 km
2nd order differencing
RK4 time differencing

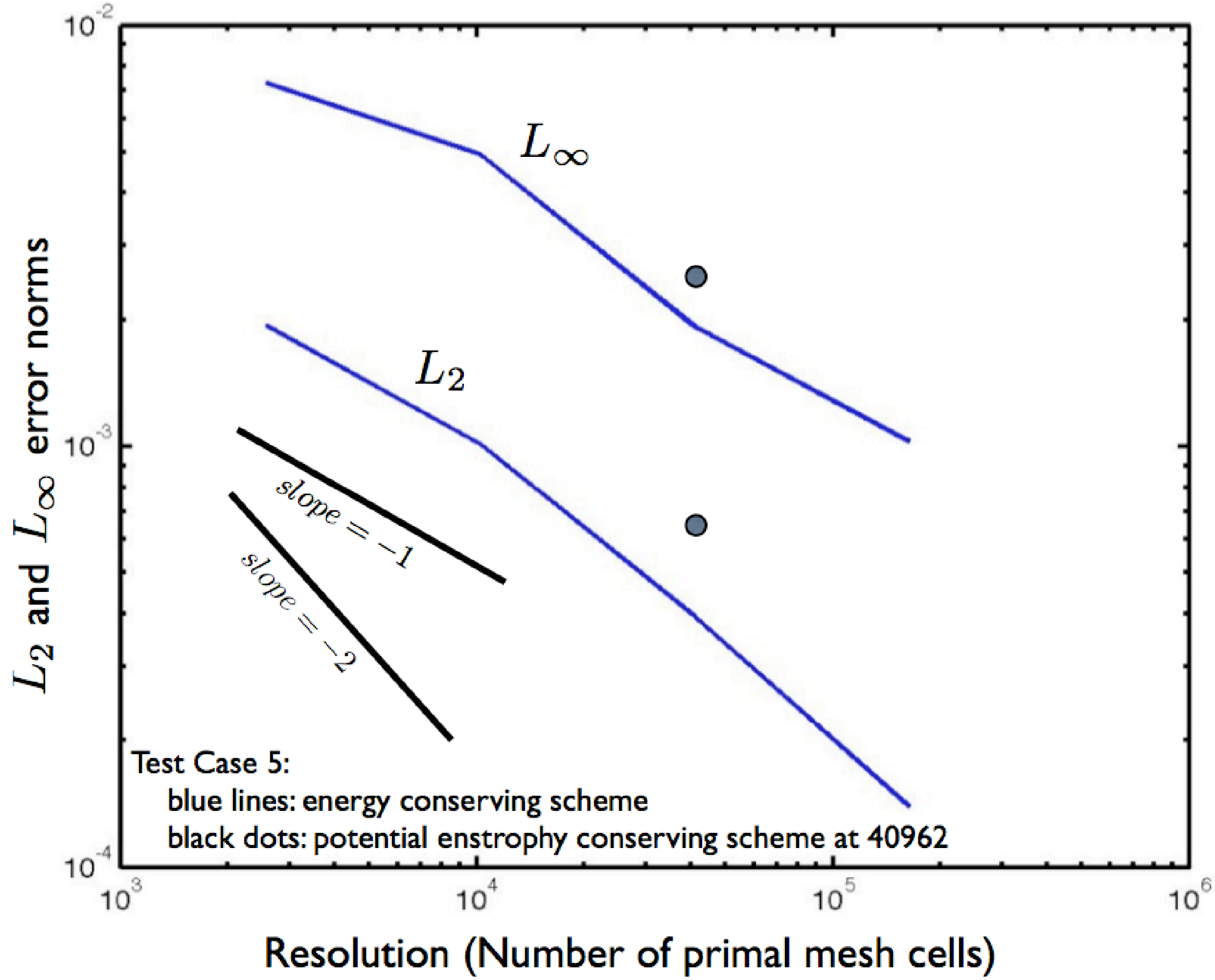




Results with quasi-uniform meshes:
New scheme is competitive
with existing models.

(Todd Ringler, LANL)

SWTC#5: Convergence Rate as Measured by L_2 and L_{inf} Norms



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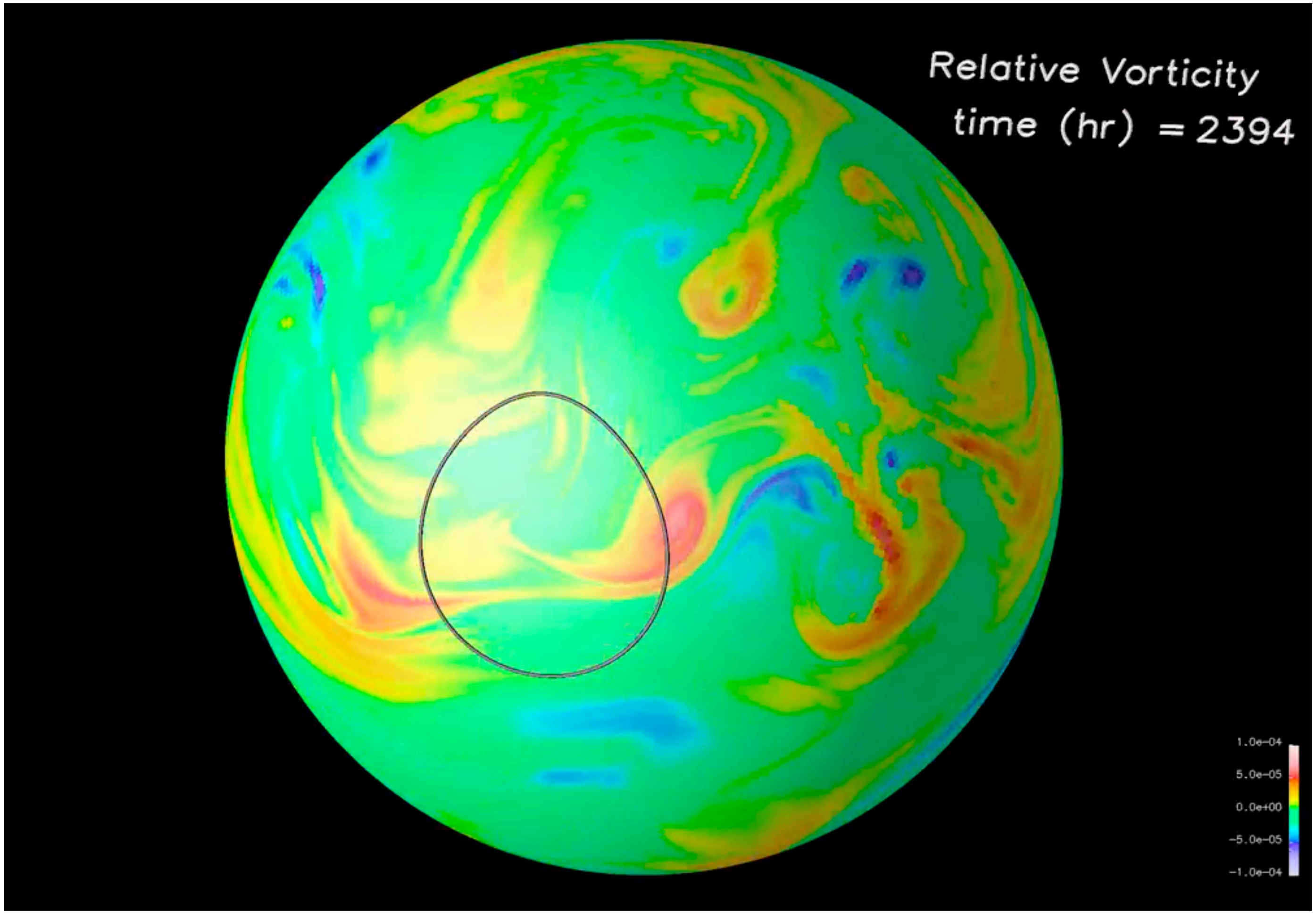
(Todd Ringler, LANL)

SWTC#5: 100 Day Integration, Variable-Res Mesh

Computing potential vorticity with an upstream bias allows potential enstrophy dissipation while conserving energy

d ~ 40 km over terrain
~ 120 km elsewhere



(Todd Ringler, LANL)

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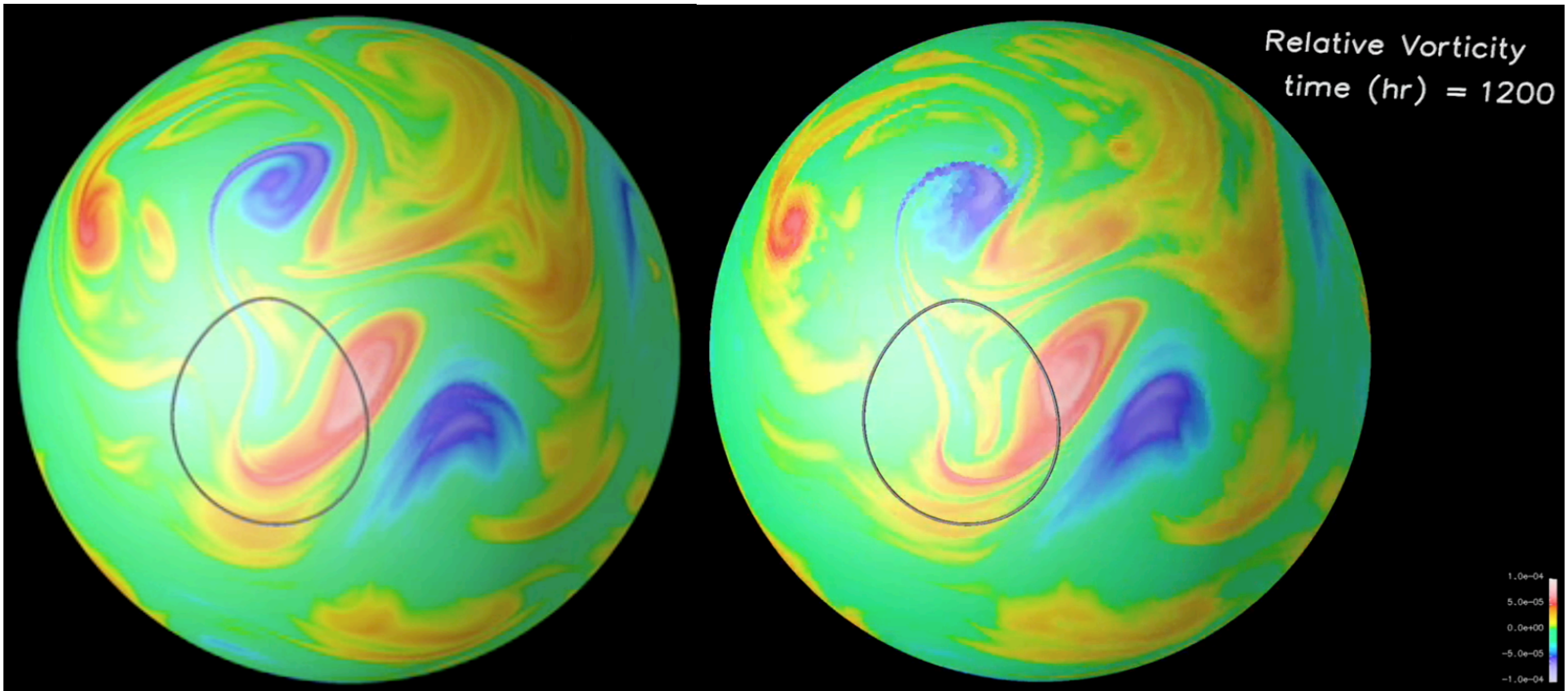
SWTC#5 Relative Vorticity at 50 Days: Impact of Variable Mesh

Energy conserving and potential enstrophy dissipating simulation



Constant mesh, d ~ 60 km   Variable Mesh, d ~ 40 - 120 km

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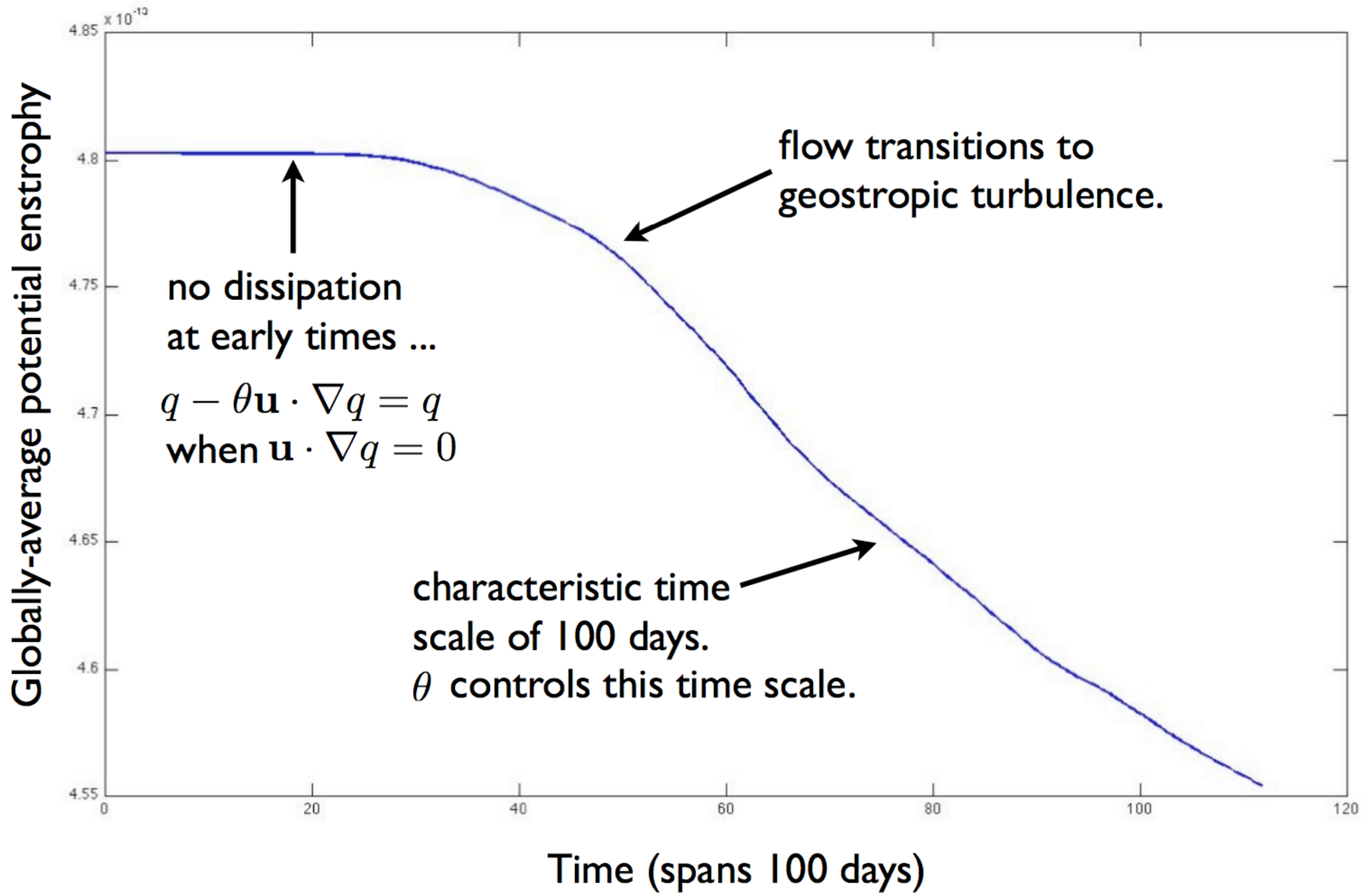
(Todd Ringler, LANL)

SWTC#5: Globally-Averaged Potential Enstrophy Evolution

Using upstream bias for potential vorticity interpolation

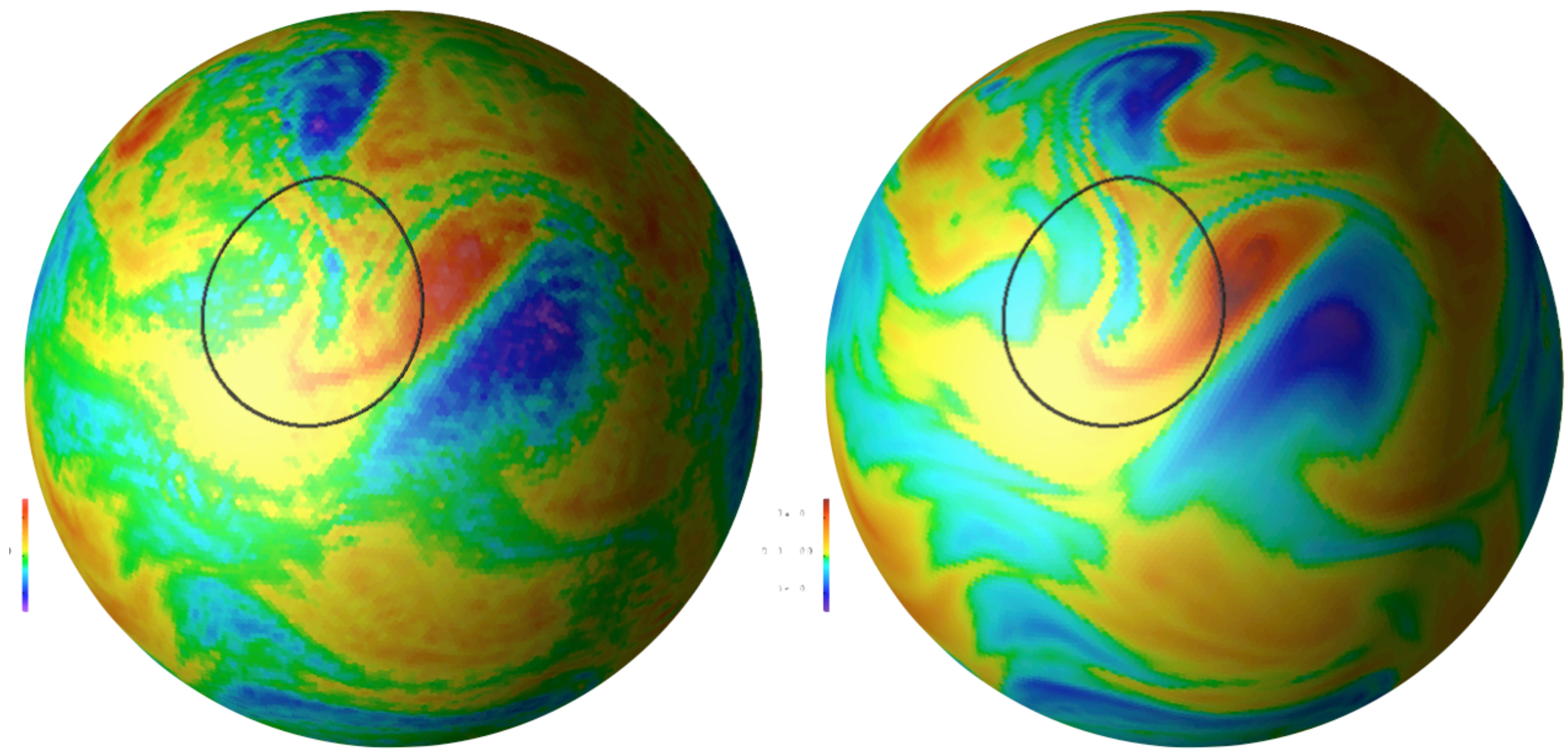


(Todd Ringler, LANL)

SWTC#5 Relative Vorticity at 50 days: Impact of Dissipating Potential Enstrophy

Enstrophy conserving - PV flux
Computed without upstream bias

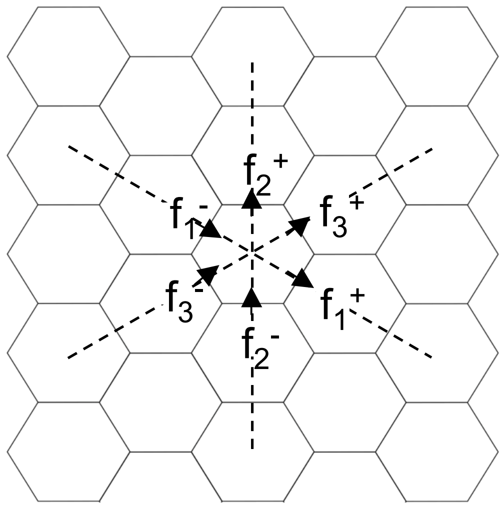
Enstrophy dissipating - PV flux
Computed with upstream bias



Both simulations conserve energy to $1e^{-8}$

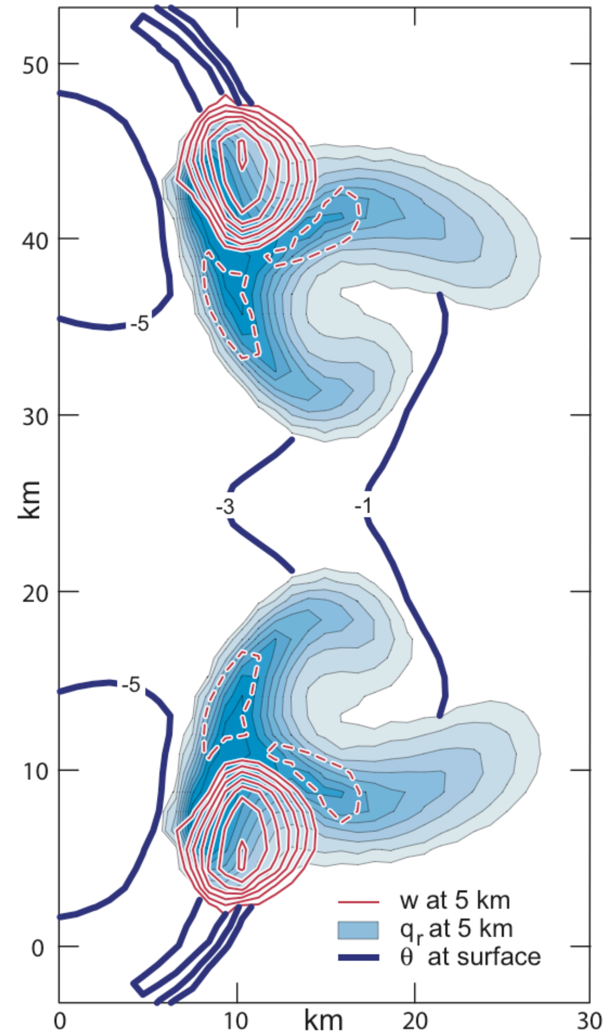
(Todd Ringler, LANL)

Limited-Area Cloud Model on Hexagonal C-Grid



Finite-Volume Fluxes on Hexagonal C-Grid

Splitting Supercell at 2 hours



1 km Hexagonal Grid Simulation

Research Progress:

- Constructed a 3-D limited-area hexagonal-grid cloud model based on WRF/ARW numerics to evaluate performance.
- Documented that hexagonal-grid cloud simulations are at least as accurate and computationally more efficient than those on a conventional rectangular grid.

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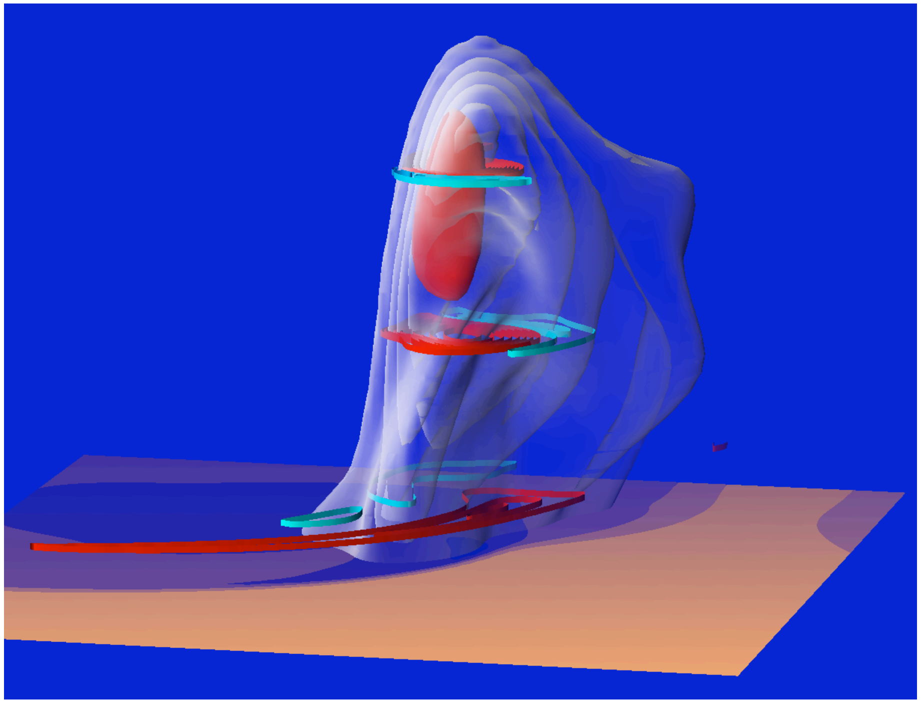
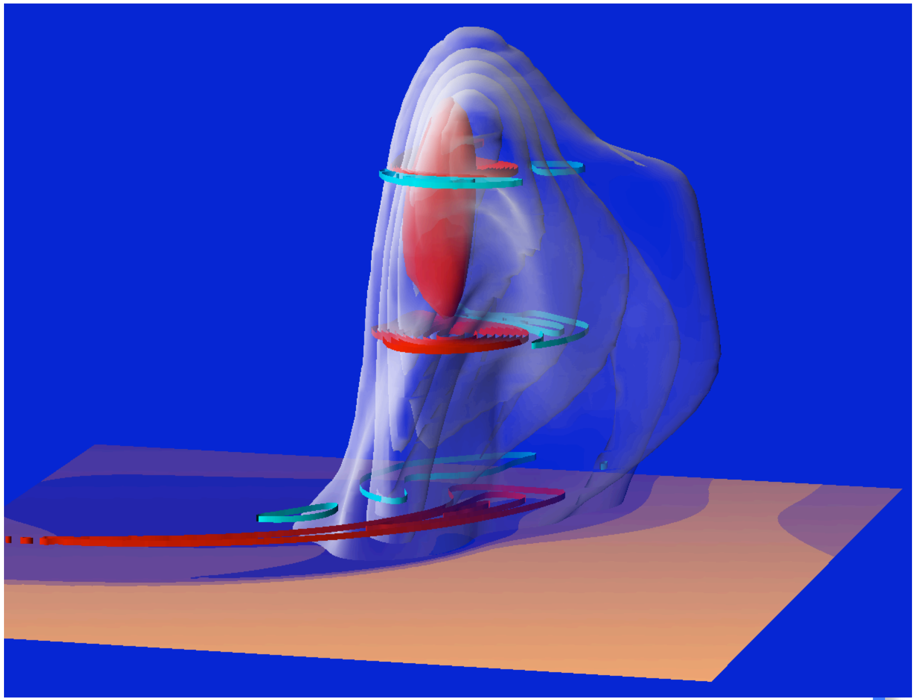
3-D Supercell Simulation ~500 m Horizontal Grid

Rectangular Grid



Hexagonal Grid



Vertical velocity contours at 1, 5, and 10 km (c.i. = 3 m/s)

30 m/s vertical velocity surface shaded in red

Rainwater surfaces shaded as transparent shells

Perturbation surface temperature shaded on baseplane

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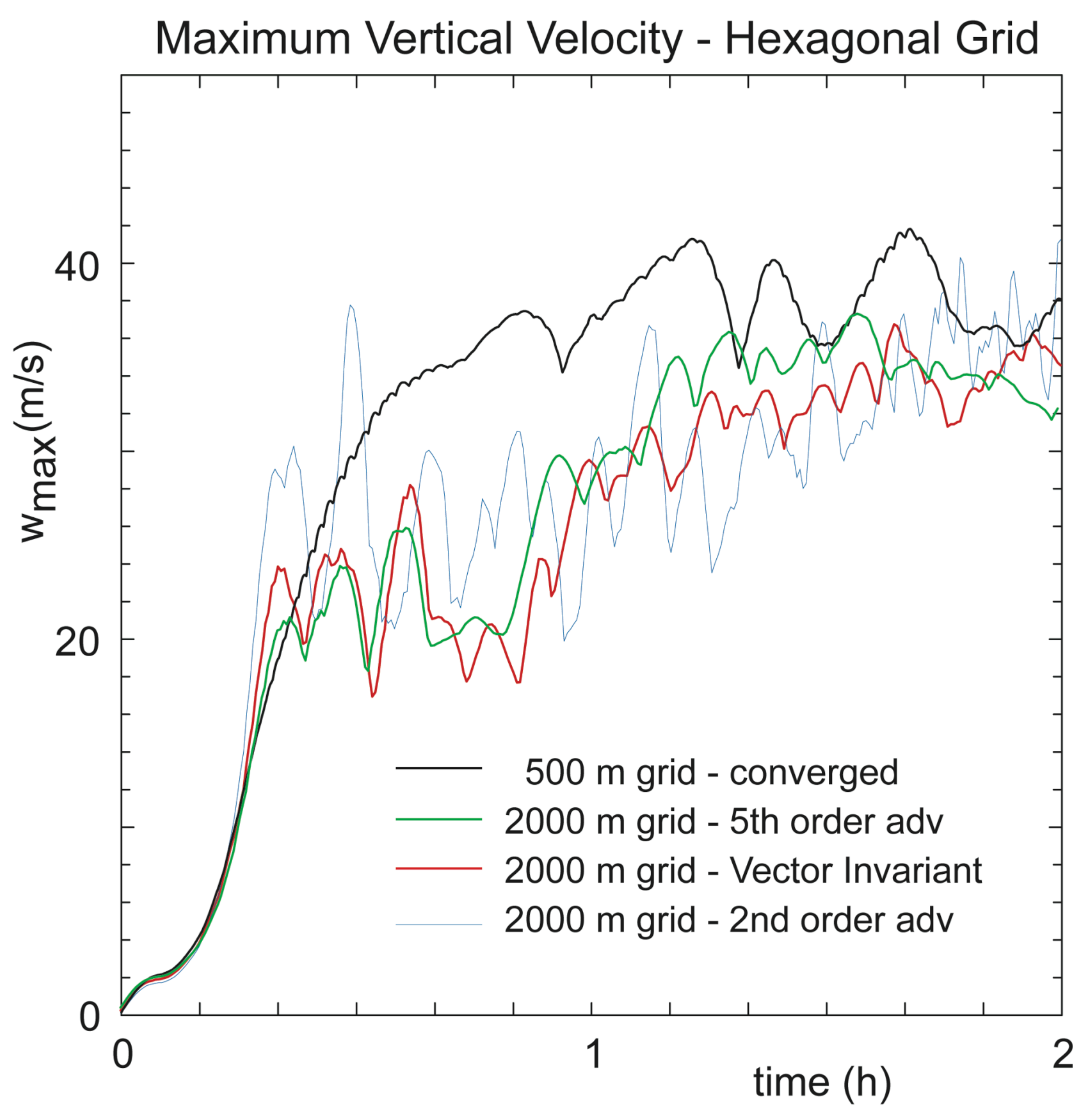
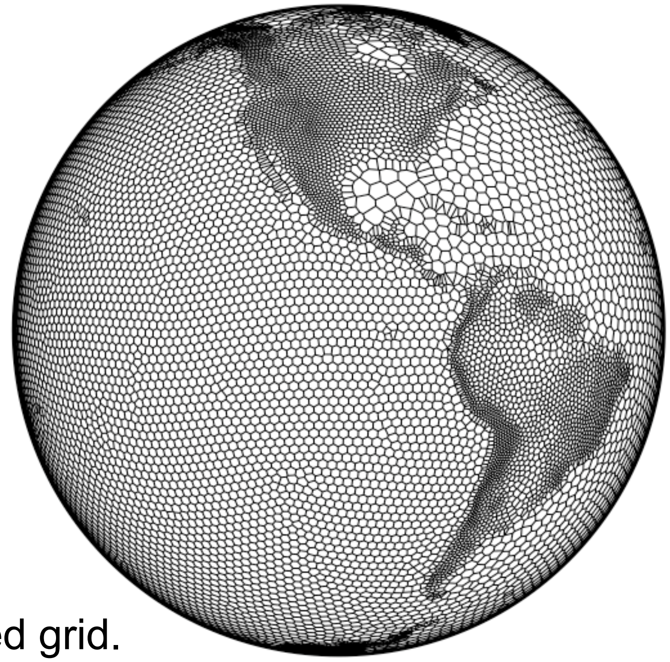
3-D Supercell Simulation - Maximum Vertical Velocity



Summary



New SW solver for SVCT C-grid

- Recovers stationary geostrophic mode.
- Conserves PV to round off.
- Conserves energy to time truncation.
- Solutions comparable to existing SW solvers, and no dissipation needed for standard SW test cases.
- Variable-resolution grid results are encouraging.
- Nonhydrostatic solver as accurate and efficient as existing cloud models
- Parallel SWL solver implemented for an unstructured grid.

Next Steps: MPAS development

- Hydrostatic 3D SVCT solver (based on SW solver).
- Nonhydrostatic solver (based on hydrostatic solver).
- Higher-order transport schemes (Bill Skamarock - next talk).
- Continued variable-resolution grid testing.

MPAS