A Baroclinic Instability Test Case on an Anelastic Dynamical Core

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Background

Although the familiar quasi-static system of equations filters sound waves, its assumption of hydrostatic balance tends to distort small-scale motions such s turbulence and convection. By neglecting the time-tendency portion of the continuity equation and considering small deviations from a hydrostatically balanced reference state, the 'anelastic' system of equations can be derived (Randall, 2010). This system still filters sound waves, but is non-hydrostatic.

An anelastic model based on the CSU icosahedral grid was developed by Hiroaki Miura. The model solves the system of equations in vorticity-divergence form:

$$\frac{\partial \delta}{\partial t} = \nabla_h \cdot (\eta \nabla_h \psi) + \mathbf{J}(\eta, \chi) - \nabla_h \cdot \left(w \left(\frac{\partial \mathbf{v_h}}{\partial z} \right) \right) - \nabla_h^2 K_h - \nabla_h^2 (c_p \theta_p \pi') + F_\delta$$

$$\frac{\partial \eta}{\partial t} = -\nabla_h \cdot (\eta \mathbf{v_h}) - \nabla_h \times \left(w \left(\frac{\partial \mathbf{v_h}}{\partial z} \right) \right) + F_\eta$$

$$\frac{\partial w}{\partial t} = -\mathbf{v_h} \cdot \nabla w + g \left(\frac{\theta'}{\theta_0} \right) - \frac{\partial}{\partial z} (c_p \theta_0 \pi') + F_w$$

$$\frac{\partial \theta}{\partial t} = -\mathbf{v_k} \cdot \nabla_h \theta - w \left(\frac{\partial \theta}{\partial z} \right) + \frac{Q}{c_p \pi_0} + F_\theta$$

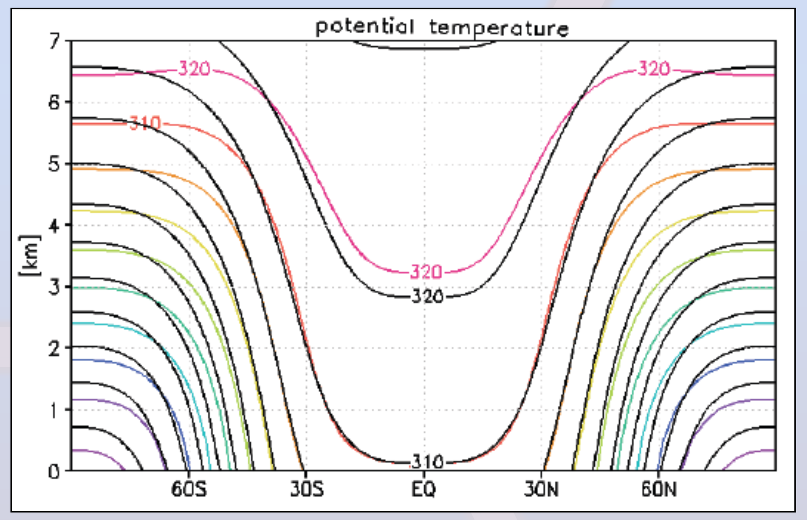
Because this system is non-hydrostatic but still filters sound waves, it scales well and is suitable for studying both large-scale processes and smaller scale ones like turbulence.

Methodology

The steady-state and baroclinic wave test cases of Jablonowski and Williamson (2006) were performed on the anelastic dynamical core and on a hydrostatic dynamical core for reference. The anelastic model was run with the following grid and timestep parameters:

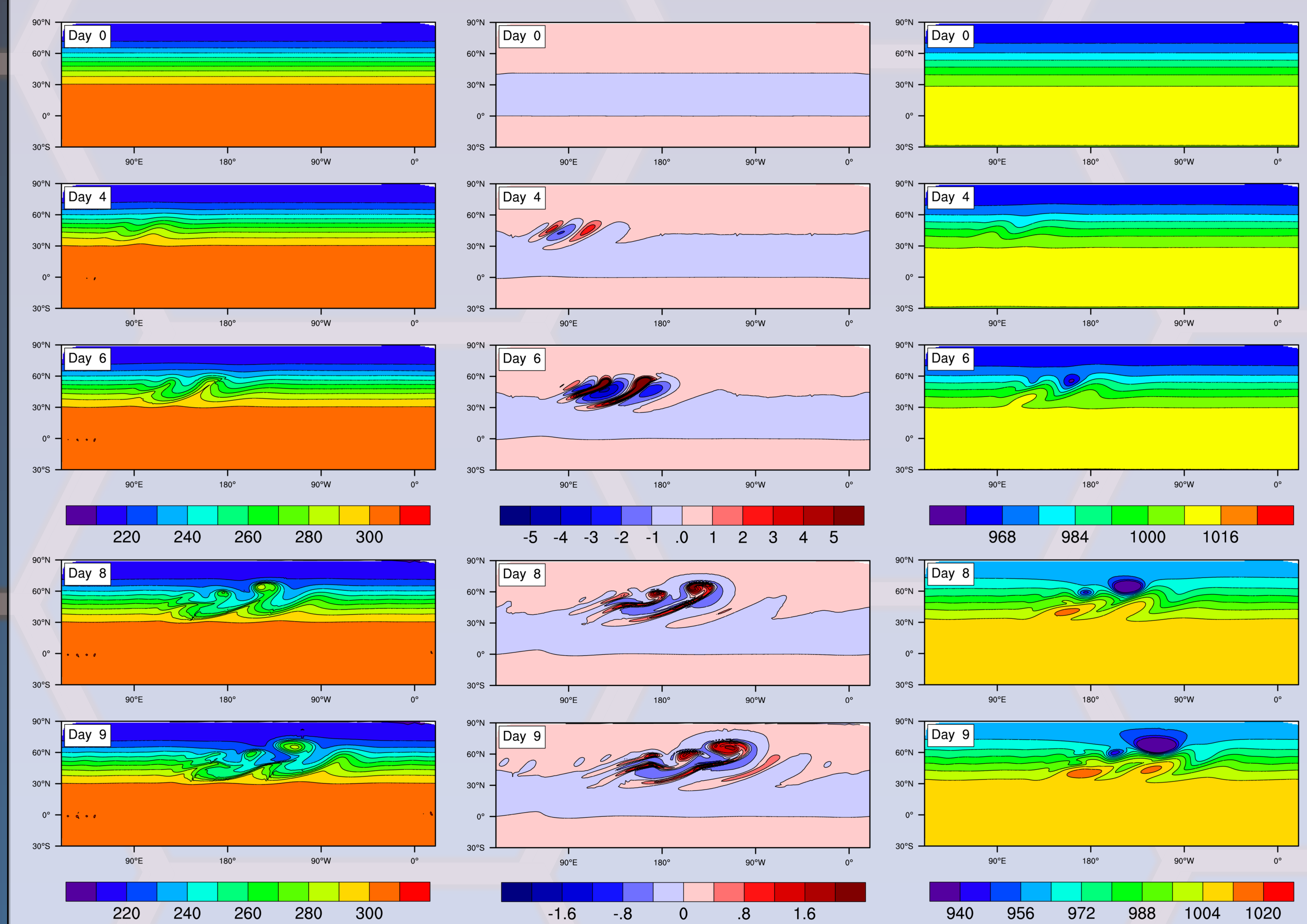
(r) # of Cells	Grid Spacing (km)	Timestep (s)
(6) 40,962	125.1	300
(7) 163,842	62.55	180

Initially, the model is set-up with prescribed, balanced initial conditions. Left unperturbed, the simulation remains in a steady state. However, a perturbation can be superimposed in the zonal wind in the northern hemisphere to trigger the evolution a baroclinic wave over several days. For use in the anelastic model, a somewhat altered initial conditions were derived by Miura (2009), as seen below in comparison to Jablonowski's:



Colored = Anelastic , Black = Original; courtesy Miura (2009)

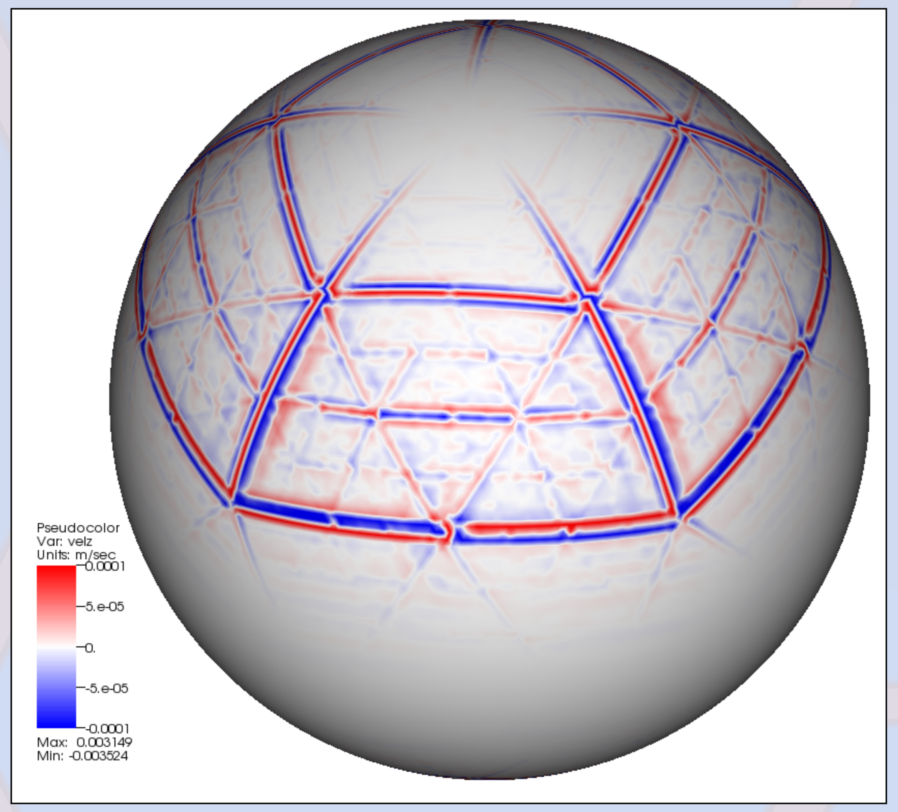
Baroclinic Wave Simulations

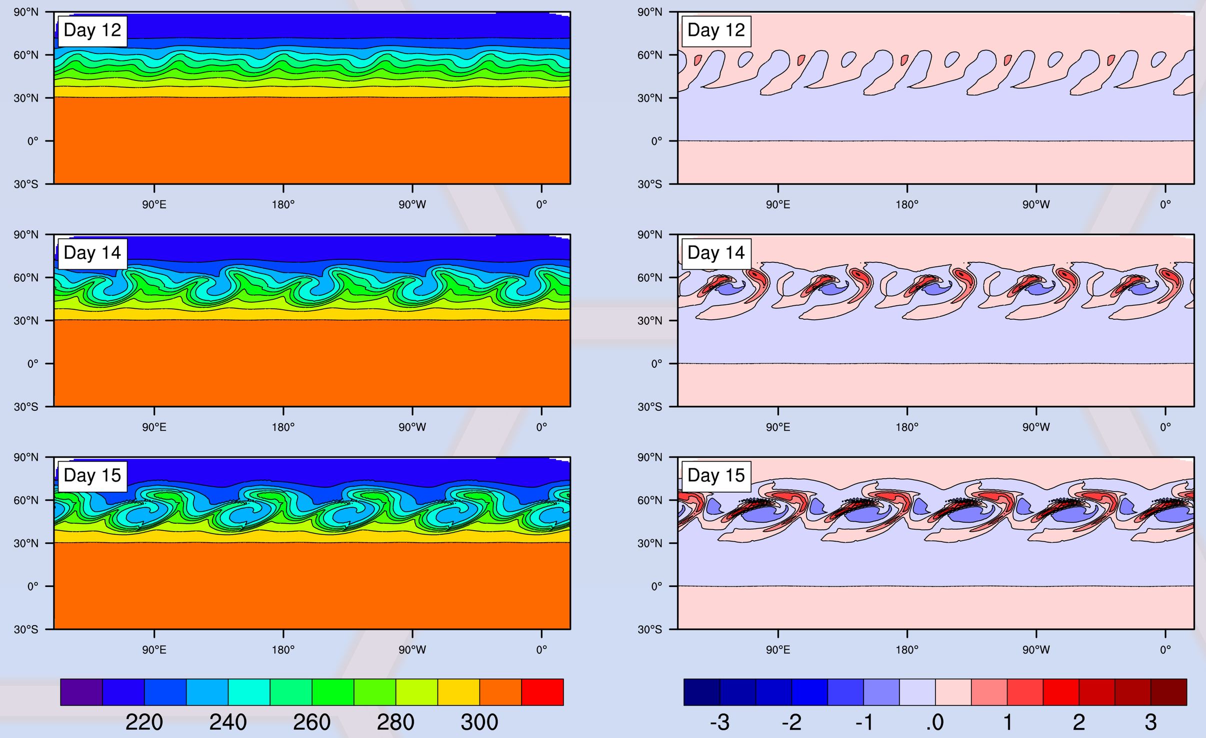


Sfc. Potential Temperature (K) | Sfc. Relative Vorticity (10^{-5}, 10^{-4} s^{-1}) | 250m Pressure (hPa)

- Performed on Z-grid anelastic dynamical core with a z-coordinate in the vertical; resolution was r6.
- By Day 6, a **large error associated with the model's grid** appears in the output.
- Error accumulates over time and **causes wave to break too early**.
- Same numerical error occurs on **both higher and lower resolution grids**, in approximately the same manner.
- Error originates at the **lowest model layer**.

Steady State Simulations





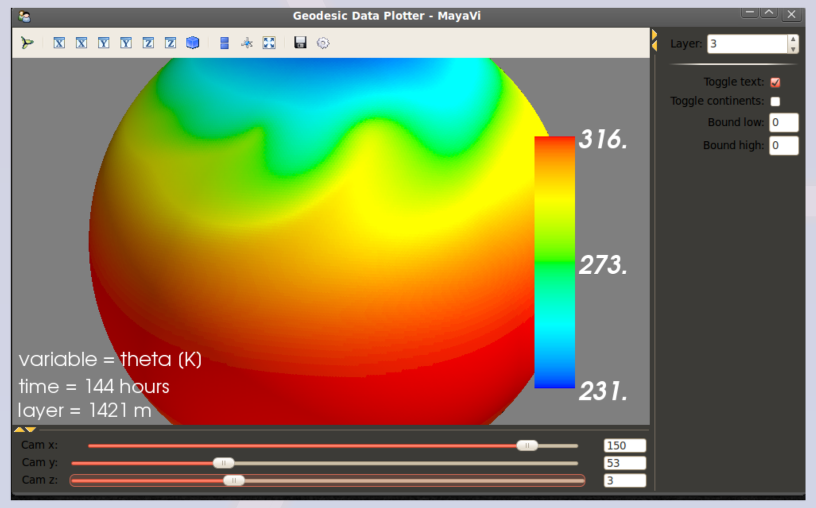
Sfc. Potential Temperature (K) | Sfc. Relative Vorticity (10^{-4} s^{-1})

- Error pattern corresponding to the geodesic grid's major seams are observed in the model's vertical velocity field.
- **Using an optimized grid** for the model **tended to reduce the magnitude of the error** and **confine it to the original icosahedron's edges.**
- After 12 days, a **pattern with wave-number 5** becomes visible in **both the northern and southern hemispheres** and grows over time.
- Symmetry in the observed pattern corresponds to the pentagonal cells in the model's computational mesh.

For more information, contact the author at dar256@cornell.edu

Visualization

A simple utility for viewing the model's Fortran binary output was developed using Python/MayaVi/TraitsUI. Built on the Enthought Python Distribution, the tool is portable and has been tested on Mac, Windows, and Linux.



Please visit http://bitbucket.org/counters/geodesic-plotter for more information.

Future Work

- Implement further grid optimizations, such as the "spring" method, to help reduce grid noise in the steady state simulation.
- Investigate errors due to approximation of the Laplacian operator by the multigrid solver in the model.
- Improve visualization toolkit and continue to develop analysis tools for working with geodesic-gridded datasets.

References

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