FV^3-GFDL: The GFDL Finite-Volume Cubed-sphere Dynamical Core

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FV^3

- Hydrostatic, shallow-atmosphere model (nonhydrostatic version in development)
- Successor to latitude-longitude FV core in NASA GEOS, GFDL AM2.1, and CAM-FV
- GFDL models
  - AM3/CM3
  - HiRAM
  - CM2.5/2.6
- CAM-FV^3
- LASG
- Academia Sinica
- GISS ModelE

FV^3 Design Philosophy

- Discretization should be guided by physical principles as much as possible
  - Finite-volume, integrated form of conservation laws
  - Upstream-biased fluxes
- Operators “reverse engineered” to achieve desired properties

Development of the FV^3 core

- Lin and Rood (1996, MWR): Flux-form advection scheme
- Lin and Rood (1997, QJ): FV shallow-water solver
- Lin (1997, QJ): FV Pressure Gradient Force
- Lin (2004, MWR): Vertically-Lagrangian discretization
- Putman and Lin (2007, JCP): Cubed-sphere advection
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Lin and Rood (1996, MWR)
Flux-form advection scheme

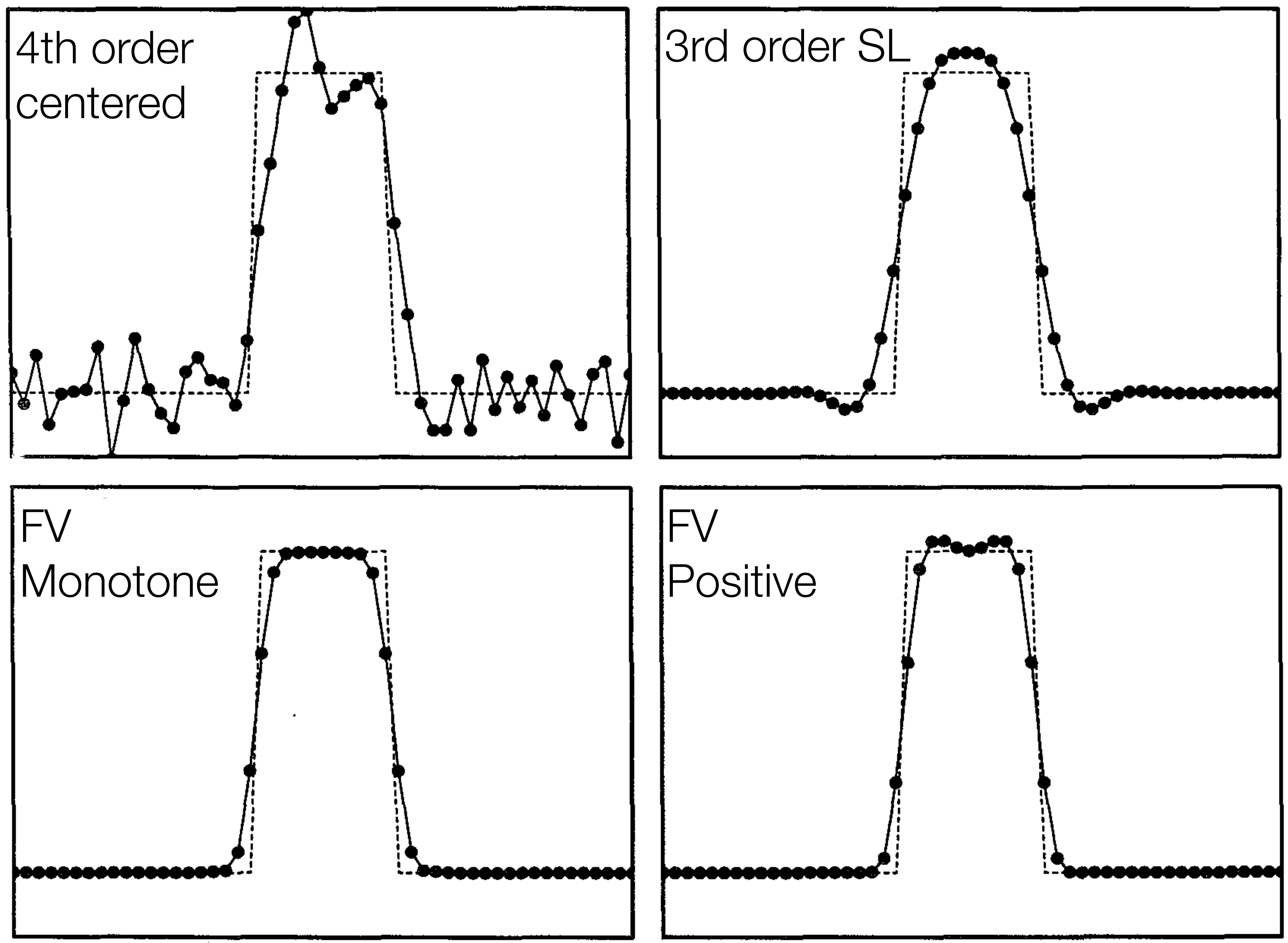
$$q^{n+1} = \frac{1}{\pi^{n+1}}\left\{\pi^n q^n + F\left[q^n + \frac{1}{2}g(q^n)\right] + G\left[q^n + \frac{1}{2}f(q^n)\right]\right\}.$$

- 2D scheme derived from 1D PPM operators
- Advective form inner operators f, g, allow elimination of leading-order deformation error
  - Allows preservation of constant tracer field under nondivergent flow
- Flux-form outer operators F, G ensure mass conservation
- All operators must be the same form to avoid Lauritzen instability

Lin and Rood (1996, MWR)
Flux-form advection scheme

- PPM operators are upwind biased
    - More physical, but also more diffusive
- Monotonicity/positivity constraint: important (implicit) source of model diffusion and noise control
    - Nonlinear constraint, “adapts” to flow state
- Scheme maintains linear correlations between tracers when unlimited or when monotonicity constraint applied (not necessarily so for positivity)

1D Advection Test



Lin and Rood 1996, MWR

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Lin and Rood (1997, QJ)
FV shallow-water solver

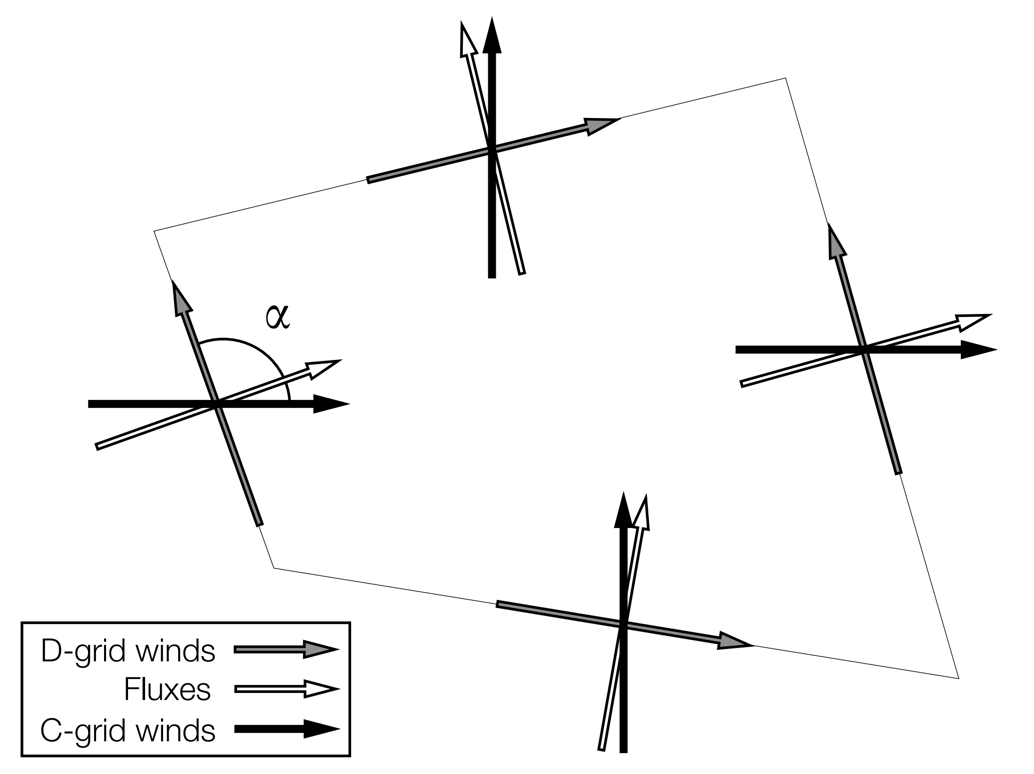
- Solves layer-averaged vector-invariant equations

$$\begin{aligned}\frac{\partial \delta p}{\partial t} + \nabla \cdot (\mathbf{V}\delta p) &= 0\\ \frac{\partial \delta p \Theta}{\partial t} + \nabla \cdot (\mathbf{V}\delta p \Theta) &= 0\end{aligned}$$

- δp is proportional to layer mass

$$\frac{\partial \mathbf{V}}{\partial t} = -\Omega \hat{k} \times \mathbf{V} - \nabla\left(\kappa + \nu \nabla^2 D\right) - \frac{1}{\rho}\nabla p\Big|_z$$

- θ: not in SW solver but is in full 3D Solver



- Forward-backward timestepping
  - PGF evaluated backward with updated pressure and height

Lin and Rood (1997, QJ) FV shallow-water solver

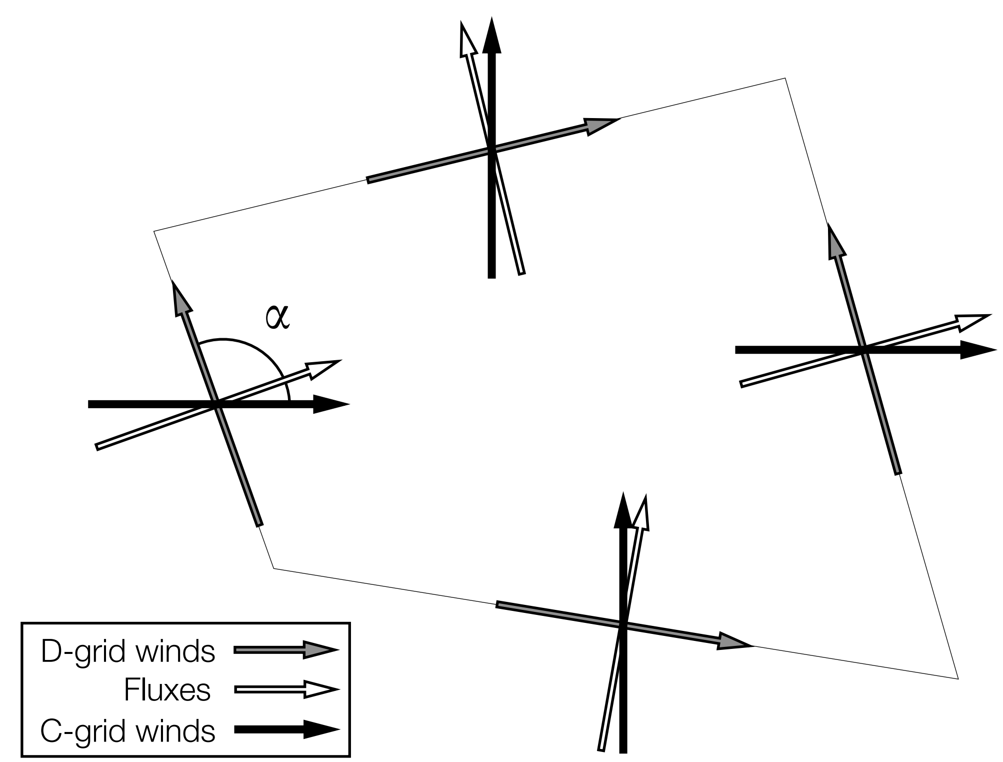
- Discretization on D-grid, with C-grid winds used to compute fluxes

$$
\begin{aligned}
\frac{\partial \delta p}{\partial t} + \nabla \cdot (\mathbf{V}\delta p) &= 0 \\
\frac{\partial \delta p \Theta}{\partial t} + \nabla \cdot (\mathbf{V}\delta p \Theta) &= 0
\end{aligned}
$$

- D-grid winds interpolated to get C-grid winds, which are stepped forward a half-step for an approx. to time-centered winds

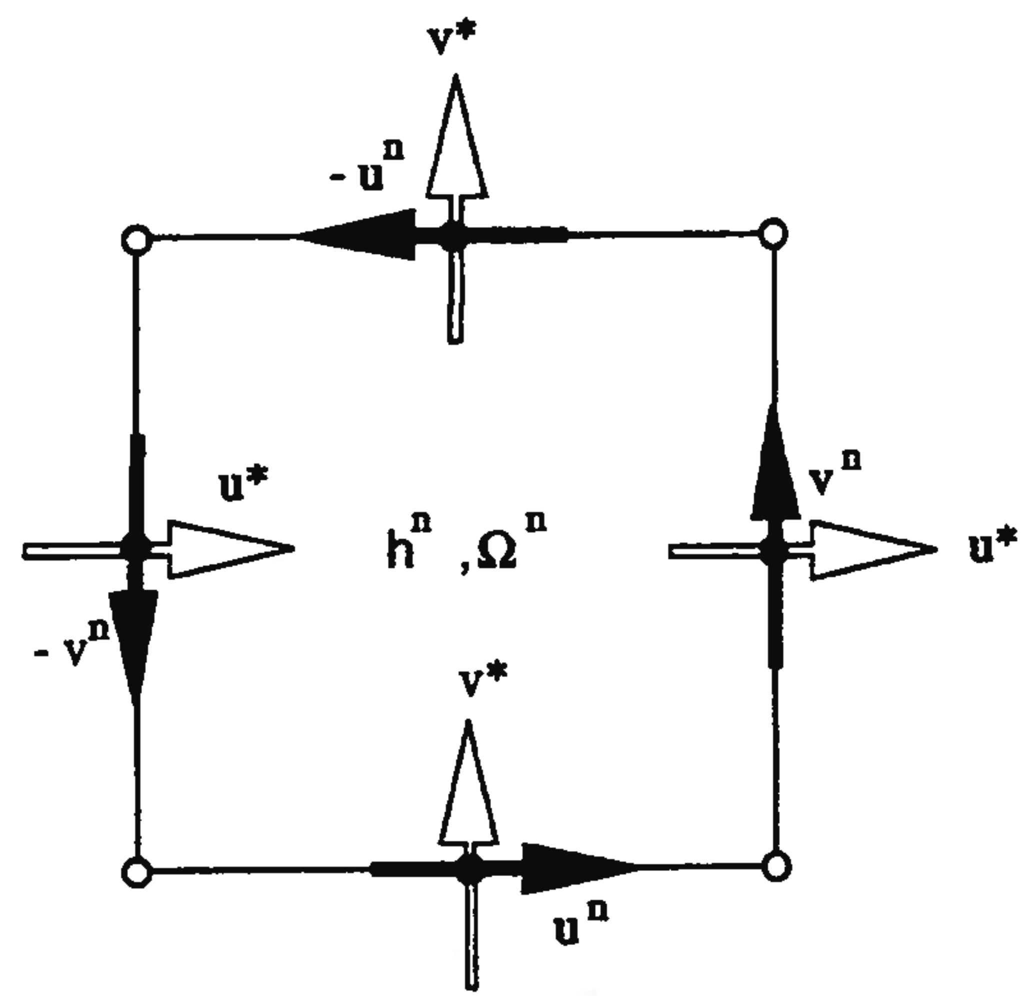
$$
\frac{\partial \mathbf{V}}{\partial t} = -\Omega \hat{k} \times \mathbf{V} - \nabla \left(\kappa + \nu \nabla^2 D\right) - \frac{1}{\rho} \nabla p \Big|_z
$$

- Two-grid discretization and time-centered fluxes avoid computational modes



FV shallow-water solver: Vorticity flux

- Nonlinear vorticity flux term in momentum equation
- D-grid allows exact computation of absolute vorticity—no averaging!
- Uses same flux as δp
  - Consistent flux of mass and vorticity improves preservation of geostrophic balance
- Advantages to this form not apparent in linear analyses



FV shallow-water solver: Kinetic Energy Gradient

- Vector-invariant equations susceptible to Hollingsworth-Kallberg instability if KE gradient not consistent with vorticity flux

- Solution: use C-grid fluxes again to advect wind components, yielding an upstream-biased kinetic energy

$$\kappa^* = \frac{1}{2}\left\{\mathscr{X}(\overline{u^*}^{\theta}, \Delta t; u^n) + \mathscr{Y}(\overline{v^*}^{\lambda}, \Delta t; v^n)\right\}.$$

    - Consistent advection again!

FV shallow-water: Polar vortex test

- Note how well strong PV gradients are maintained

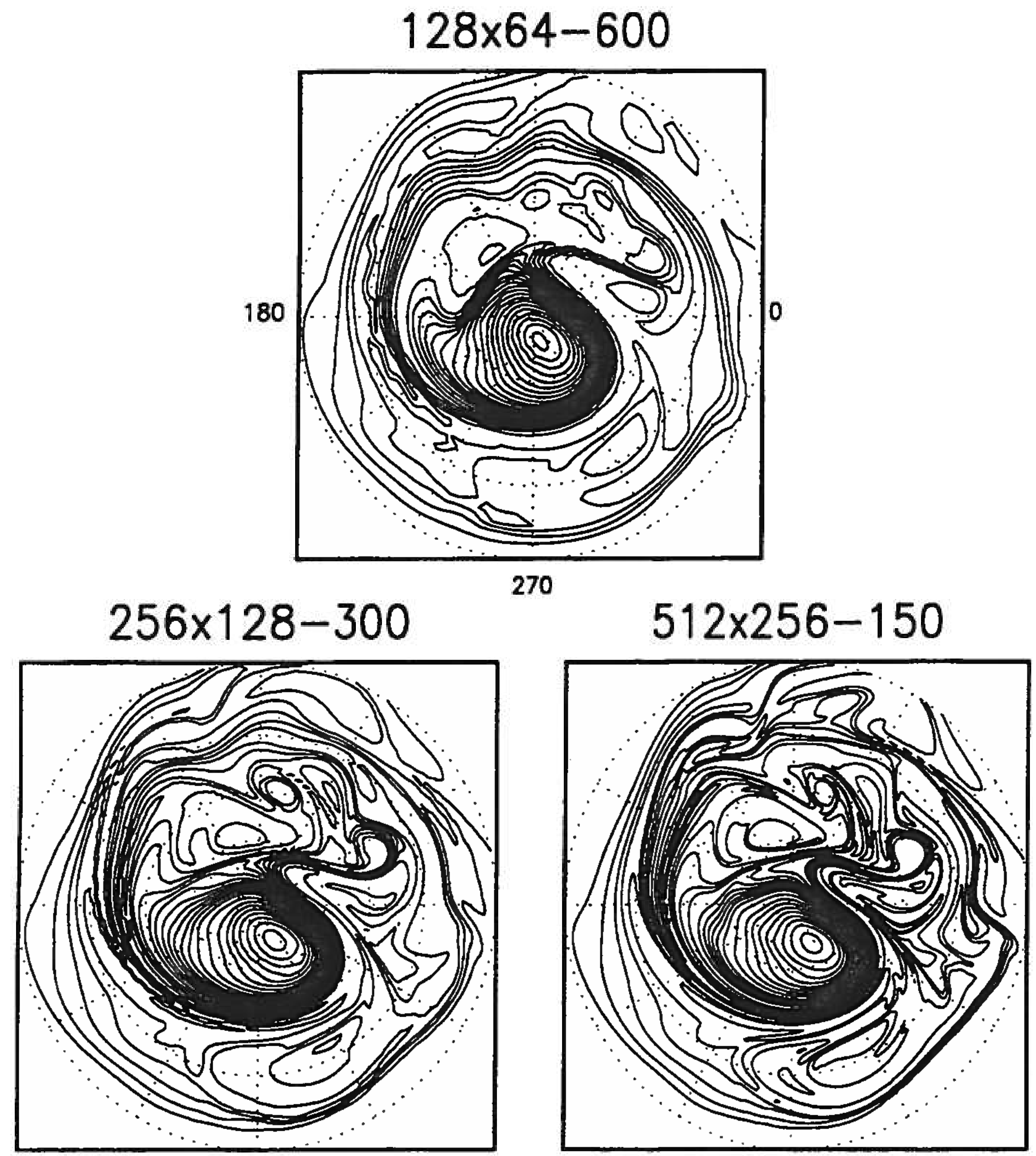


Figure 10. Polar stereographic projection (from the equator to the north pole) of the potential vorticity contours at DAY-24 in the 'stratospheric vortex erosion' test case at three different resolutions.

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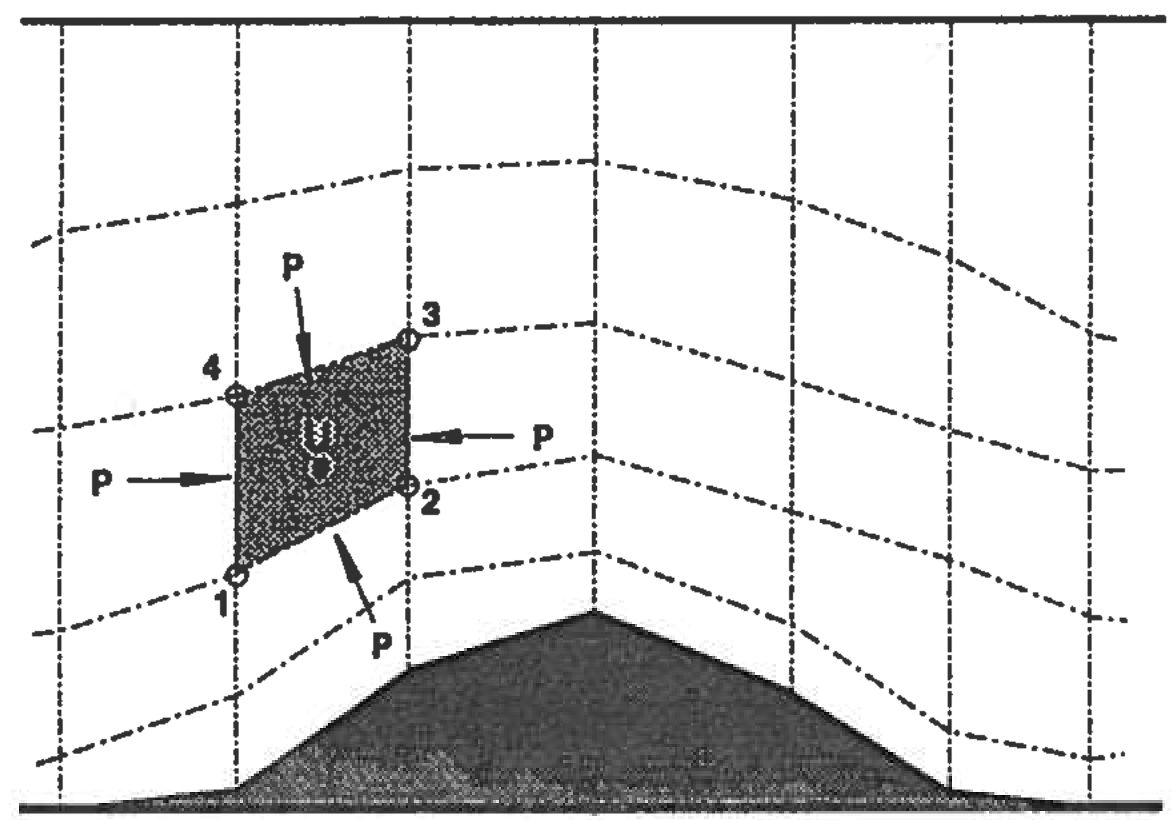
Lin (1997, QJ)
Finite-Volume Pressure Gradient Force

- Computed from Newton's second law and Green's Theorem



$$\left(\frac{\mathrm{d}u}{\mathrm{d}t}, \frac{\mathrm{d}w}{\mathrm{d}t}\right) = \frac{1}{\Delta m}(\Sigma \mathbf{F}_x, \Sigma \mathbf{F}_z)$$

$$\Sigma \mathbf{F} = \int_C P\mathbf{n}\,\mathrm{d}s$$

$$\frac{\mathrm{d}u}{\mathrm{d}t} = g\frac{\Sigma \mathbf{F}_x}{\Sigma \mathbf{F}_z} = g/\tan\gamma$$

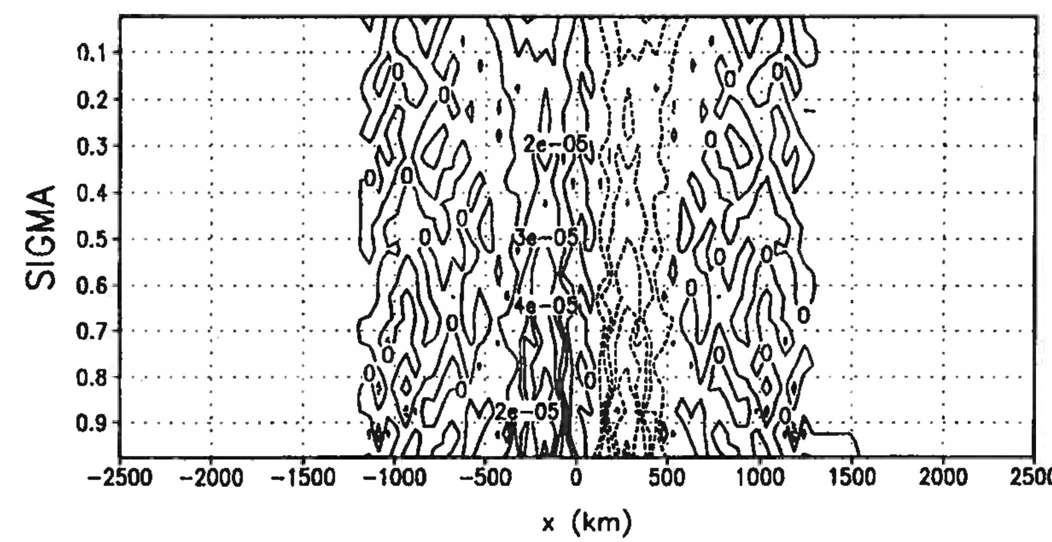
Lin (1997, QJ)
Finite-Volume Pressure Gradient Force

- Errors lower, with much less noise, compared to a finite-difference pressure gradient evaluation

- Linear line-integral evaluation used in example yields larger errors near model top

    - Now using fourth-order scheme to evaluate line integrals

Finite-Difference method



Finite-Volume method

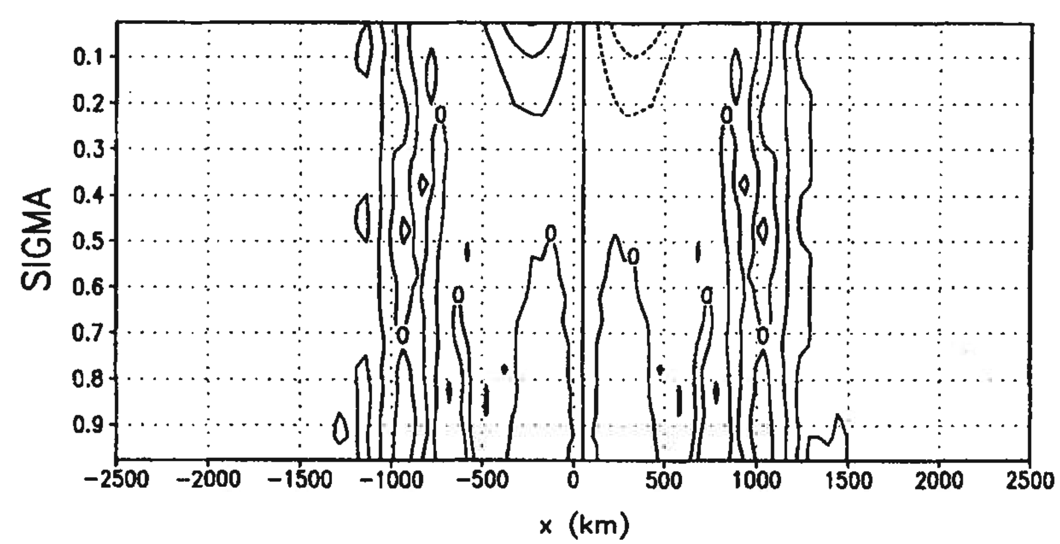


Figure 6. As in Fig. 5, but for the finite-volume method.

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Lin (2004, MWR)
Vertically-Lagrangian Discretization

- Equations of motion are vertically-integrated to yield a series of layers
- Layers like shallow-water except θ is active
- Layers deform freely while horizontal equations integrated
    - Only cross-layer interaction here is through pressure force

Vertical remapping

- To perform vertical transport, and to avoid layers from becoming infinitesimally thin, we periodically remap to an Eulerian vertical coordinate
- Implicit cubic spline for remapping accuracy
  - Implicit in vertical, so no message passing
- Remapping conserves mass and momentum
  - Option to remap total energy as well, as well as to apply an energy fixer
- Vertical remapping is computationally expensive, but only needs to be done a few times an hour

FV^3 and the GFDL models

- Terrain following pressure coordinate: $p_k = a_k + b_k p_s$
  - Other coordinates possible eg. hybrid-isentropic
- Divergence damping: the other model dissipation process
  - Fourth-order damping now standard
- Physics coupling is time-split
  - Vertical diffusion implicit and coupled to land/ocean models

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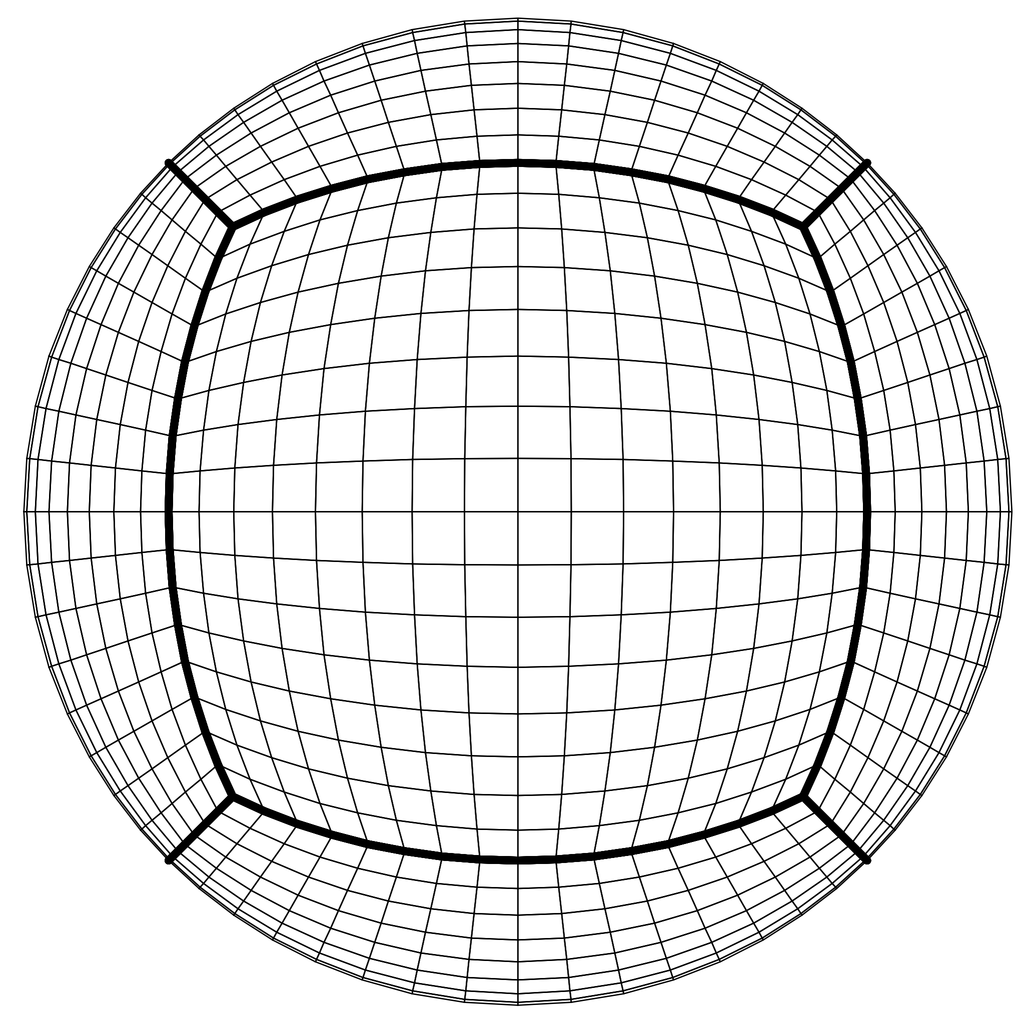
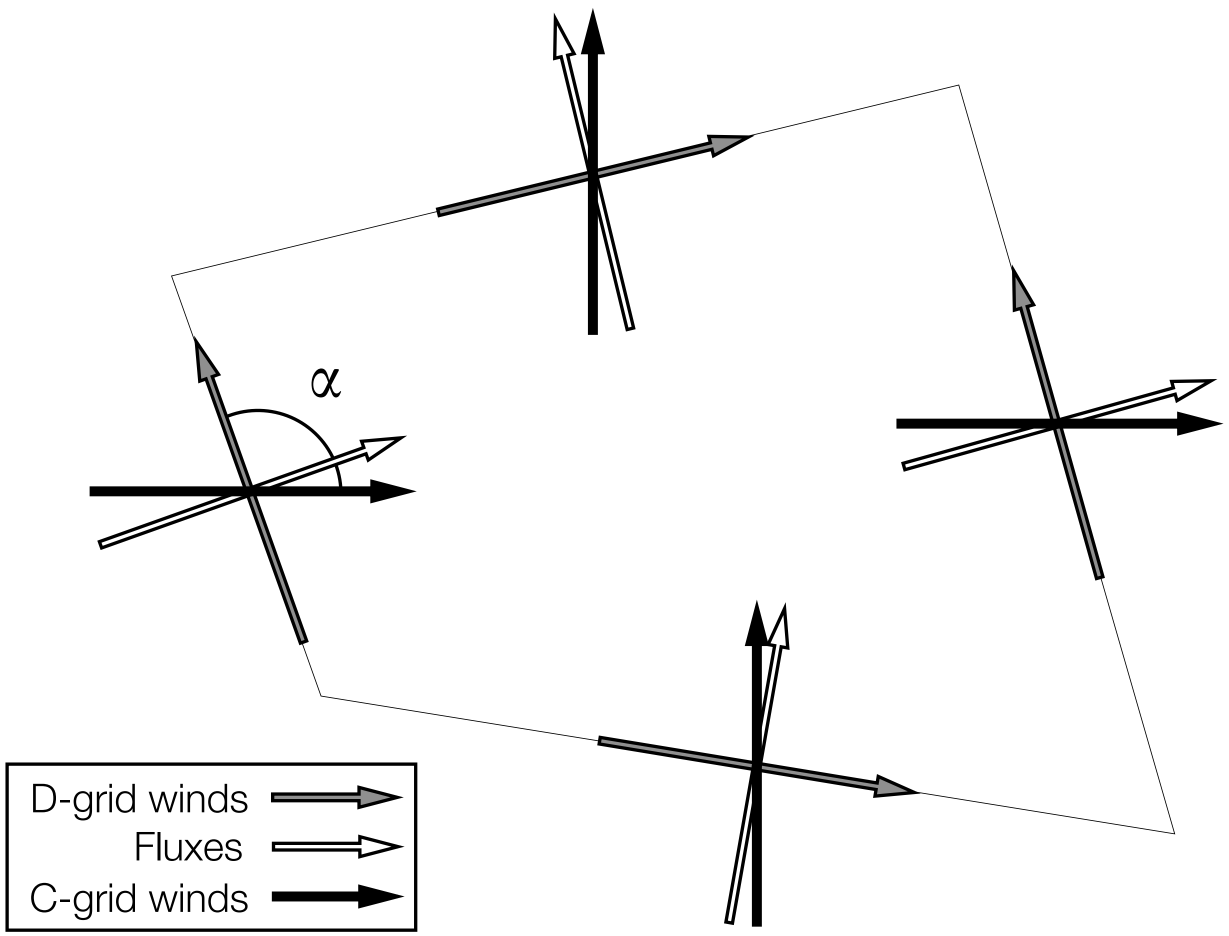
Putman and Lin (2007, JCP) Cubed-sphere advection

- Gnomonic cubed-sphere grid
    - Coordinates are great circles
- Widest cell only $\sqrt{2}$ wider than narrowest
    - More uniform than conformal, elliptic, or spring-dynamics cubed spheres
- Tradeoff: coordinate is non-orthogonal



Putman and Lin (2007, JCP)
Non-orthogonal coordinate

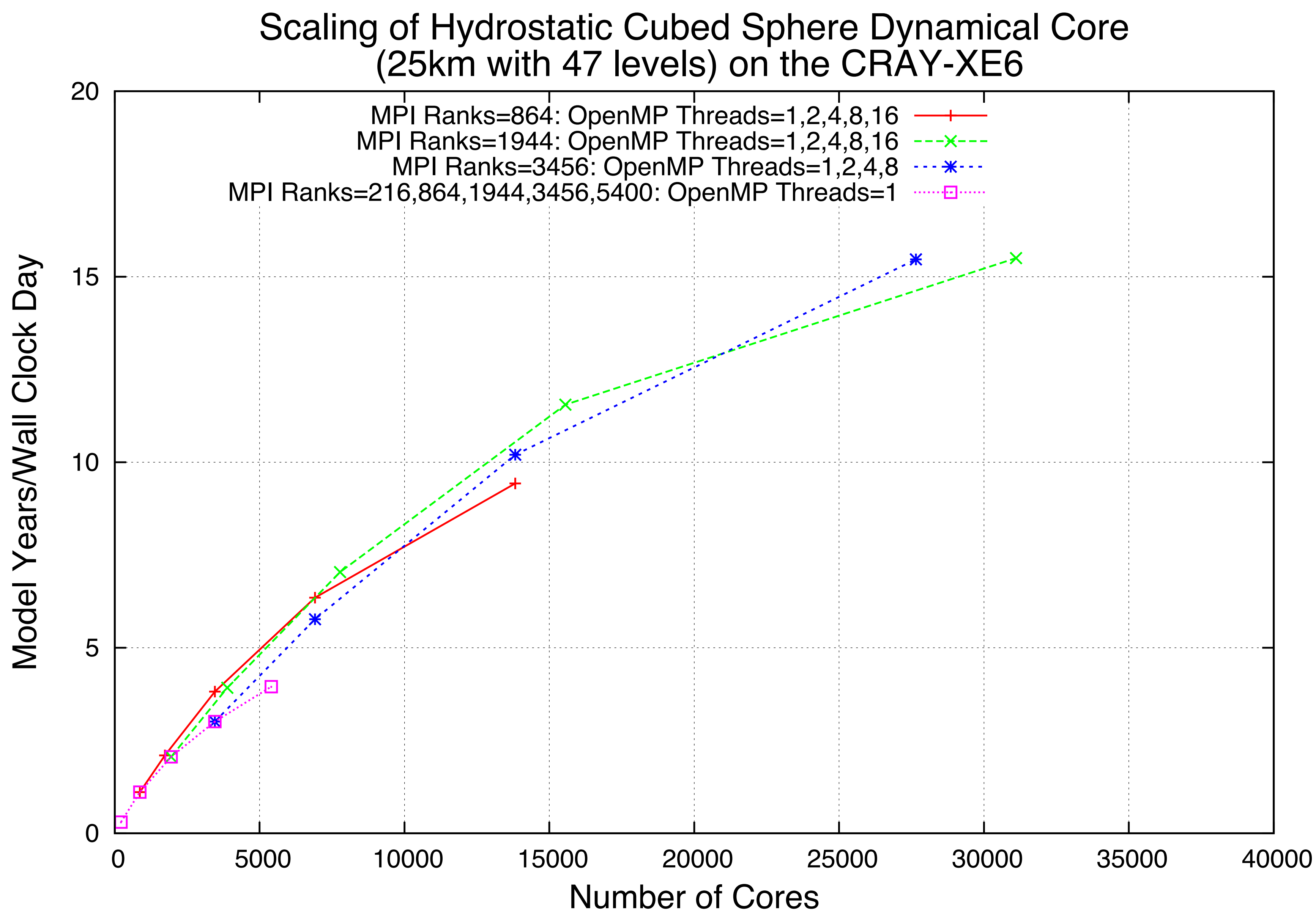
- Gnomonic cubed-sphere is non-orthogonal
- Instead of using numerous metric terms, use covariant and contravariant winds
    - Solution winds are covariant
    - Advection is by contravariant winds
    - KE is product of the two



Cubed-sphere edge handling

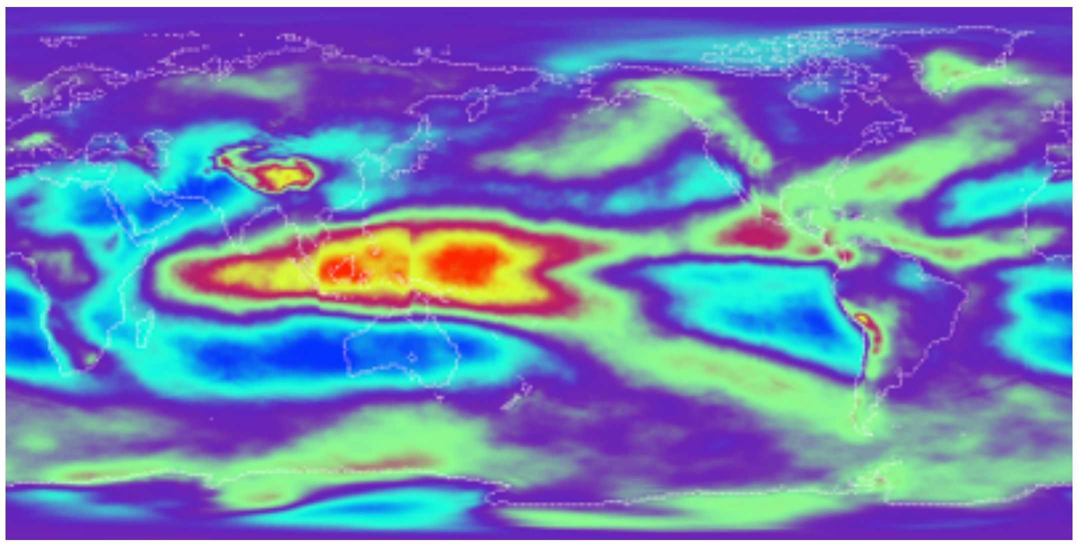
- Fluxes need to be the same across edges to preserve mass-conservation
- Gnomonic cubed sphere has ‘kink’ in coordinates at edge
- Currently getting edge values through two-sided linear extrapolation
- More sophisticated edge handling in progress

Cubed-sphere scaling

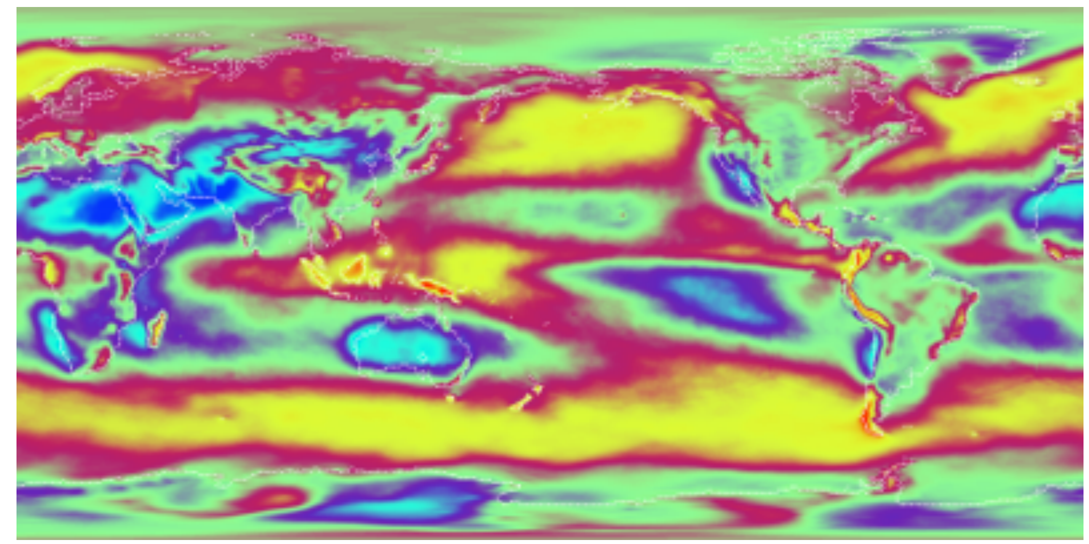


Grid nesting:
Maritime continent 3:1 nest, c90 coarse grid

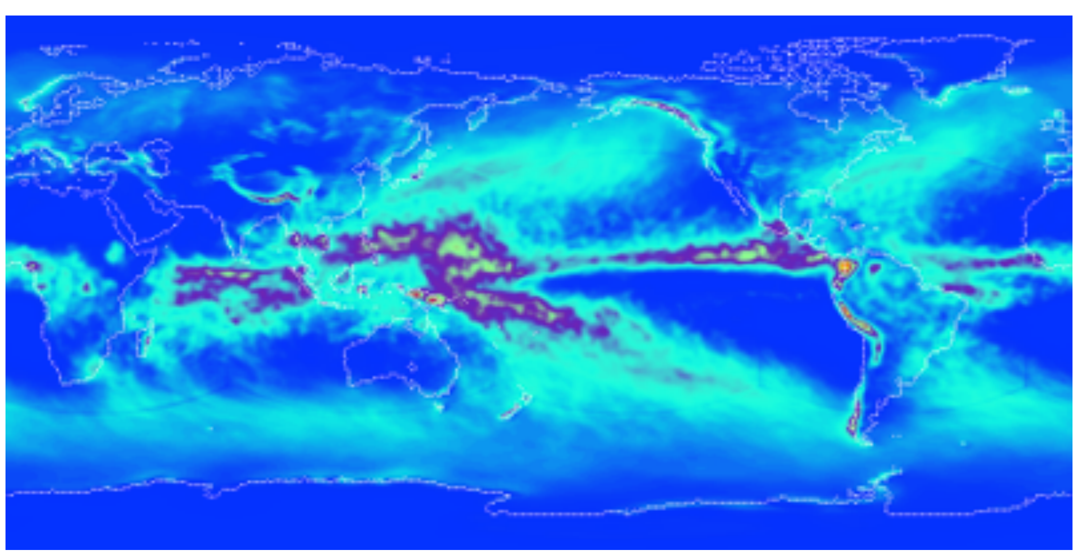
High cloud amount



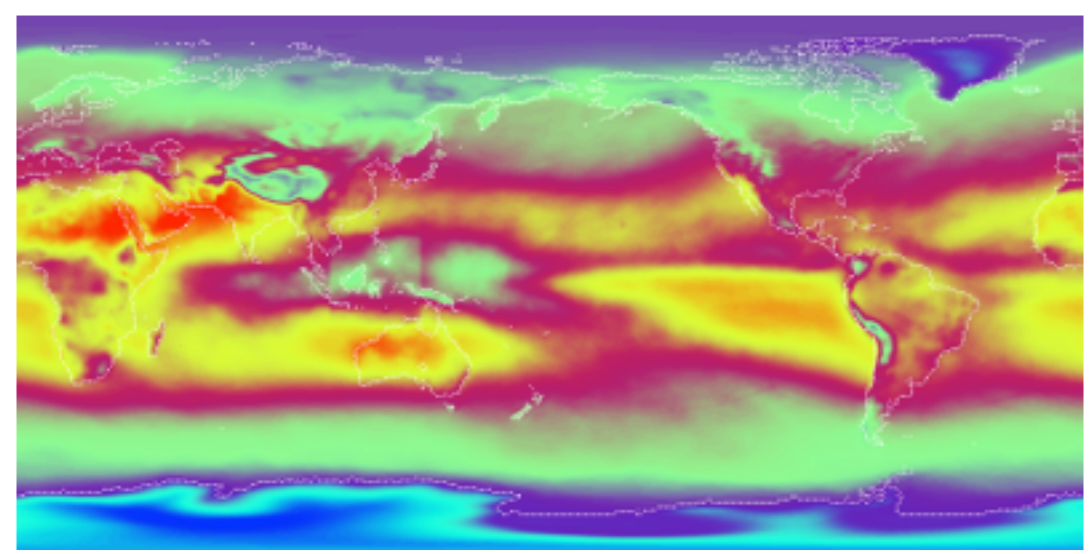
Total cloud amount



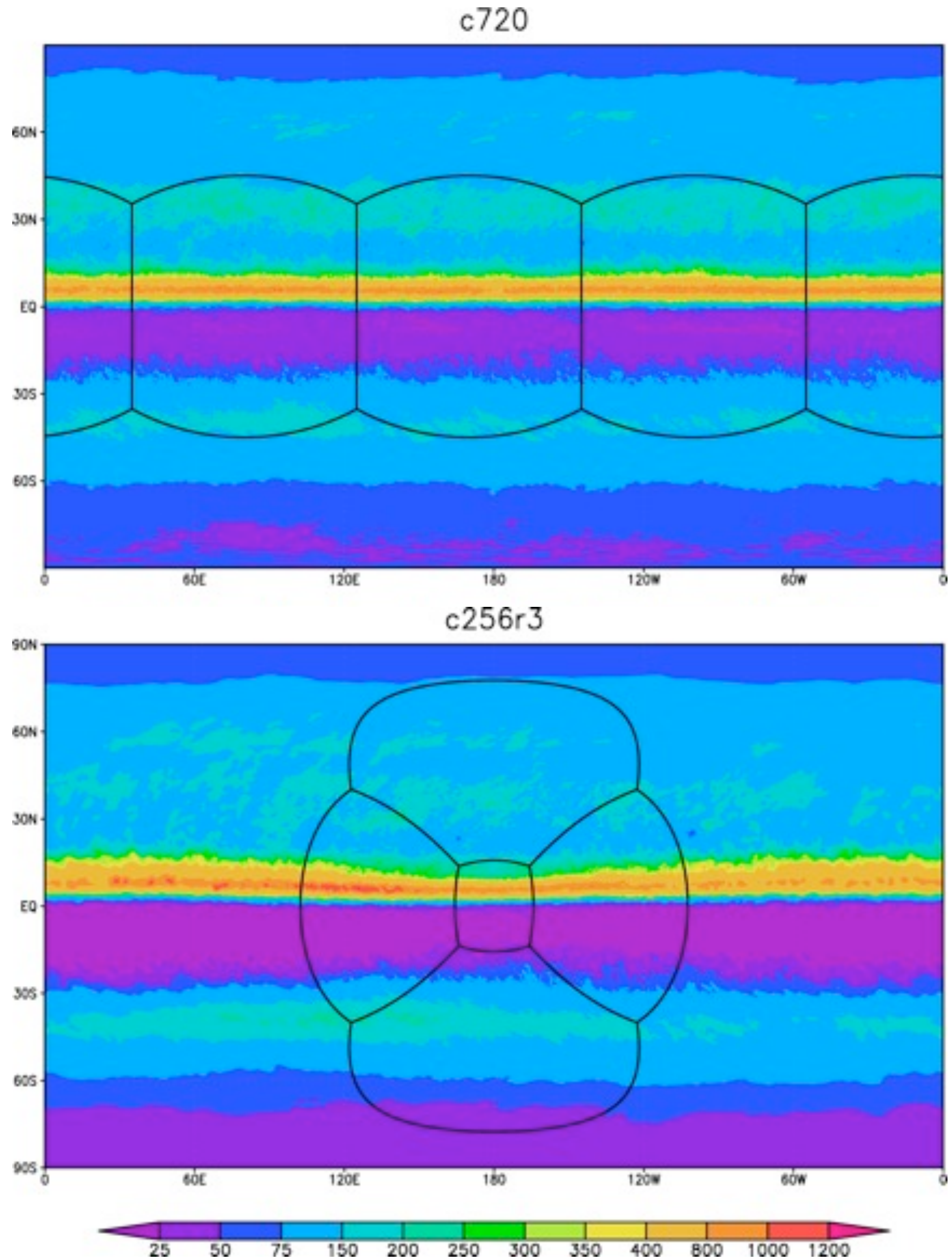
Precipitation

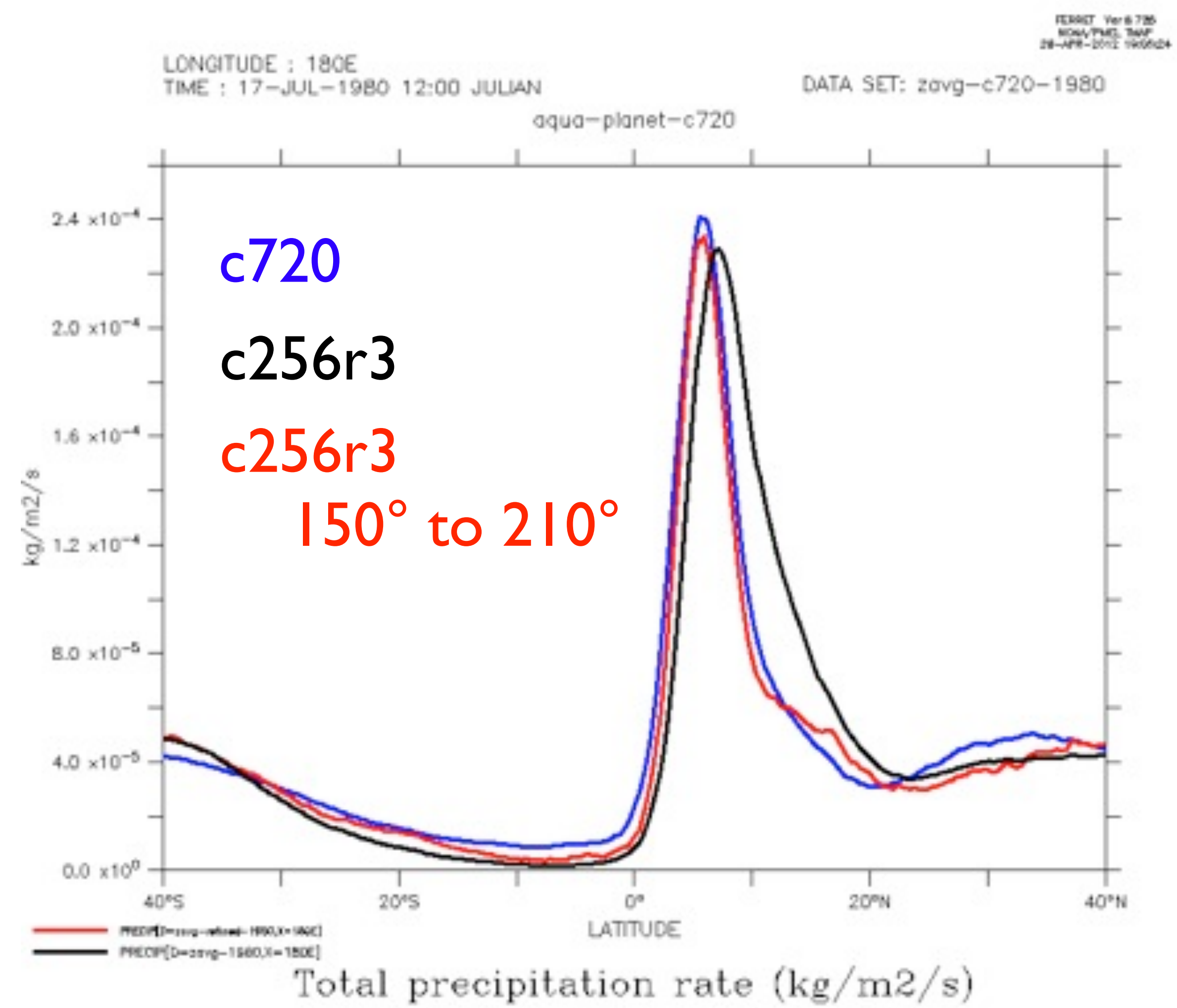


OLR



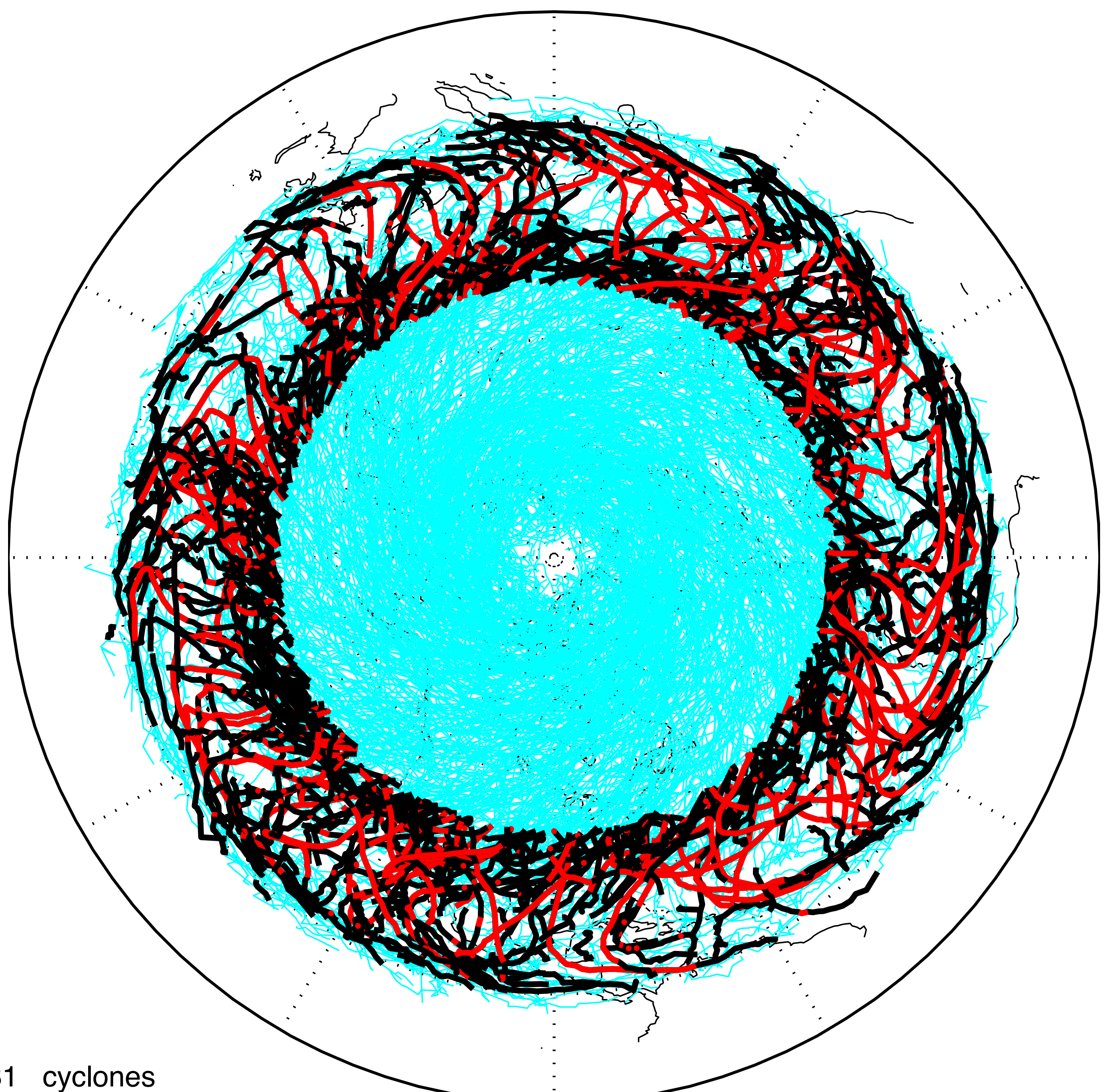
Stretched-grid aquaplanet Precipitation





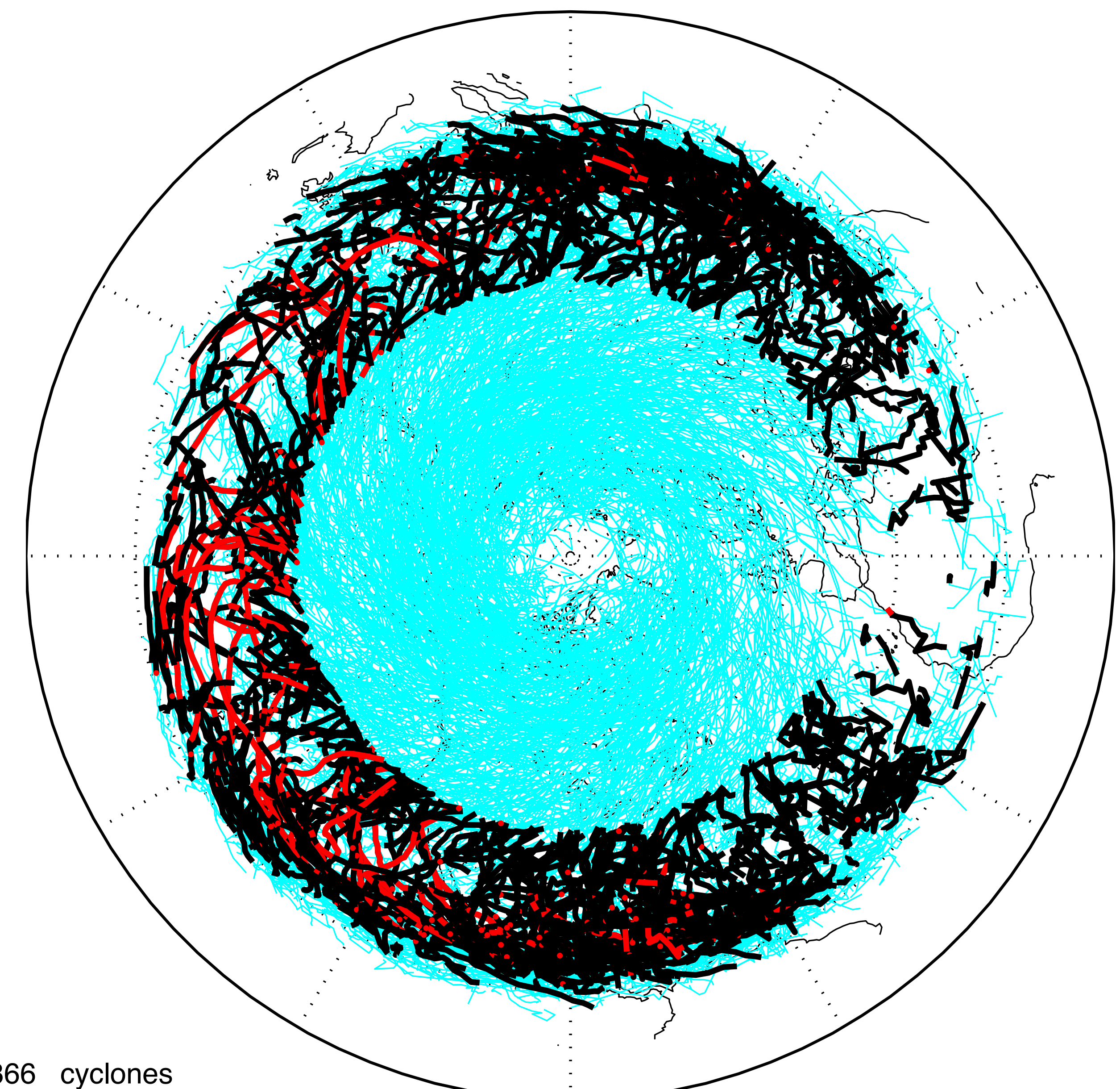
Stretched-grid aquaplanet
Tropical Cyclones

c720



2681 cyclones
513 17.5 m/s
263 32.5 m/s

c256r3



2866 cyclones
722 17.5 m/s
206 32.5 m/s