Adaptive Grids for Atmospheric General Circulation Models

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NCAR ASP Colloquium,
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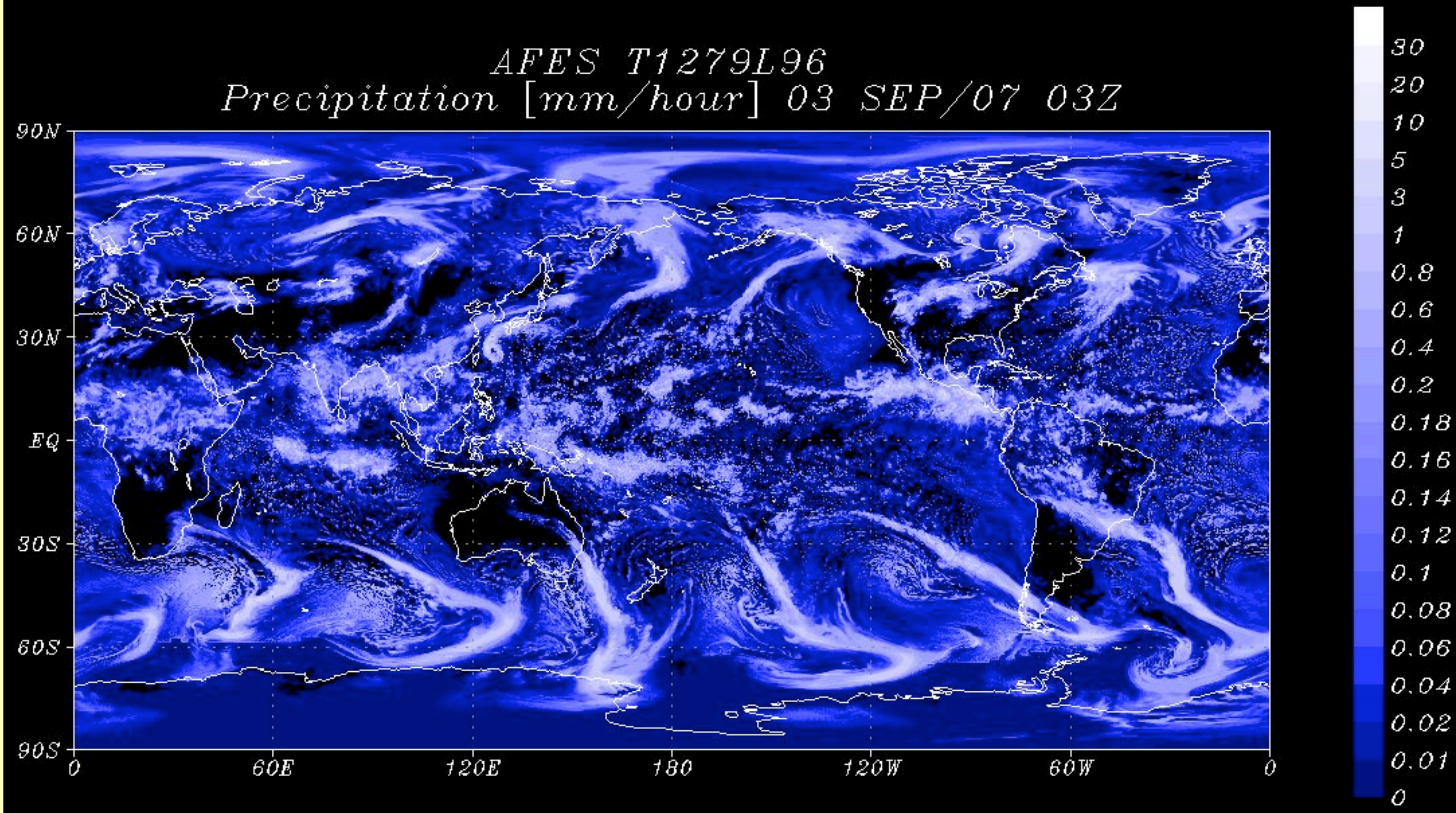
Multi-Scale Processes



Some observations

- Typical length scale of
  - Rossby waves in midlatitudes: O(10,000-1,000 km)
  - Meso-scale systems, e.g. mountain waves: O(100 km)
  - Convective cloud clusters / thunderstorms: O(10 km)
  - Single clouds, convection: O(1 km)
  - Hail ?
  - Rain droplet ?
  - Molecular diffusion ?
- Typical resolution of today's global weather and climate models: horizontal Δx, vertical ?
- 'Resolved' features are typically of order 6 Δx

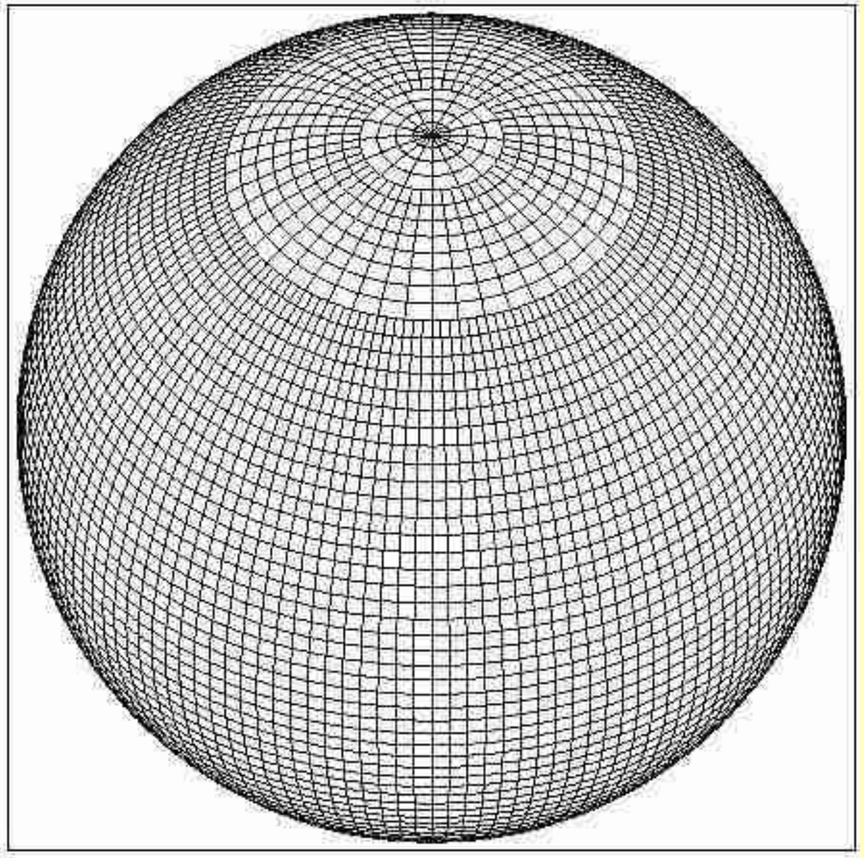
More observations

- Atmospheric flow transitions from the hydrostatic to the nonhydrostatic regime at scales around $\Delta x \approx 10$ km
- Our ‘dream’ resolutions for global weather and climate models are cloud-resolving and lie around $\Delta x \approx 1$ km
- Doubling the horizontal resolution increases the computational costs by a factor of 8
- Doubling the vertical resolutions adds another factor of 2
- We need to increase our computational power by a factor of ≈ 10,000
- and we need to be more creative:
  - invent new algorithms
  - apply Adaptive Mesh Refinement (AMR) to bridge the gap soon

Adaptive Grids for 3D Atmospheric Models

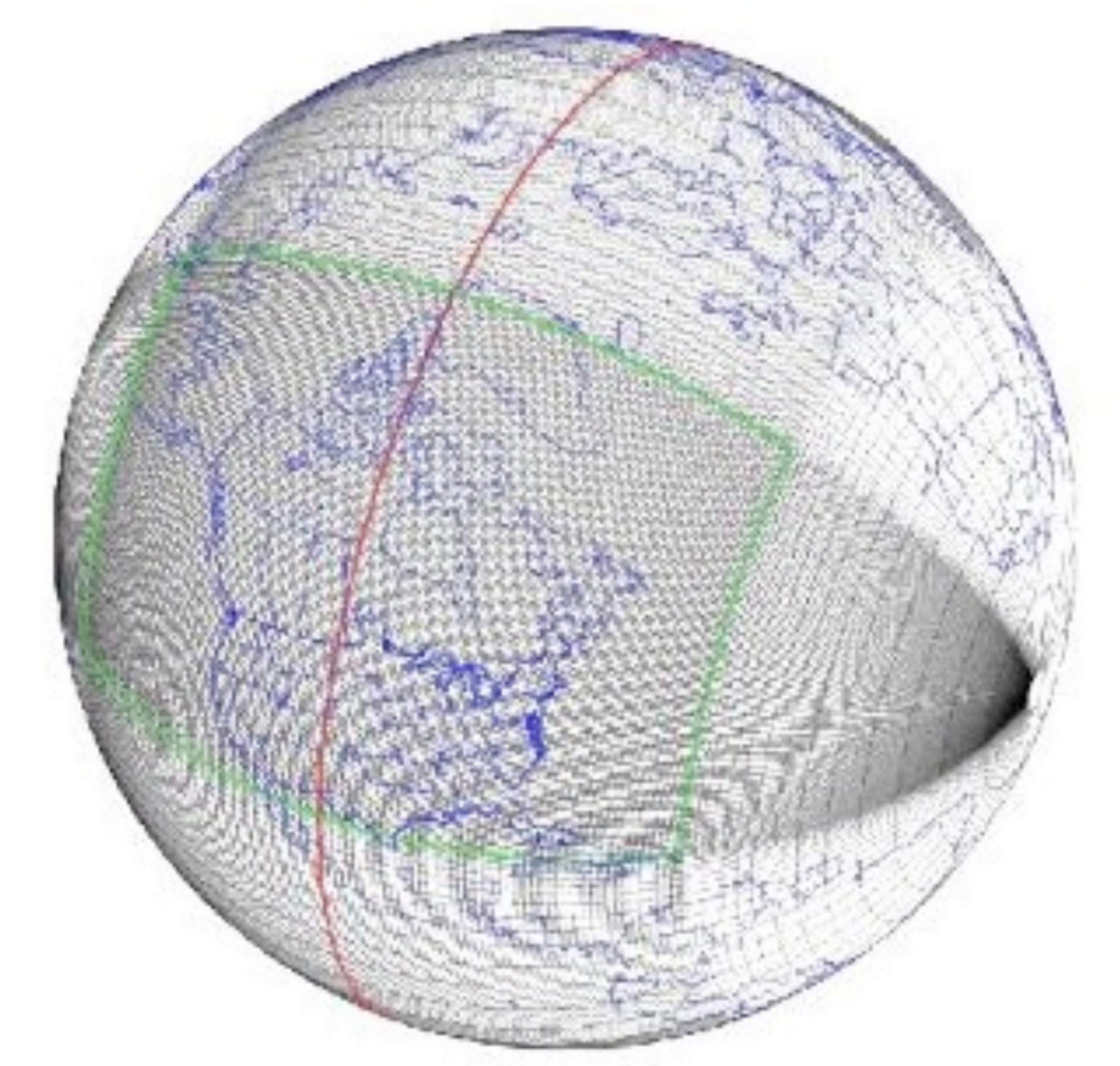
- Statically adaptive grids
  - Reduced grid
  - Stretched grids
  - Transformed grids (e.g. Schmidt coordinate transformation)
  - Unstructured grids
  - Nested grids
- Dynamically adaptive grids
  - Irregular data structures: triangulated grids (Bacon et al., MWR 1998, Gopalakrishnan et al., MWR 2002)
  - Regular data structures: block-structured lat-lon grid (Skamarock et al., JCP 1989, Hubbard and Nikiforadis, MWR 2003, Jablonowski et al., MWR 2006)
  - Cubed sphere with spectral element formulation: A. St-Cyr, S. Thomas and J. Dennis (St-Cyr et al., MWR (2008))

Static Adaptations: Reduced Grids



- Number of grid cells in longitudinal direction is reduced towards high latitudes
- Keeps the resolution more uniform, allows longer time steps

Static Adaptations: Stretched Grids

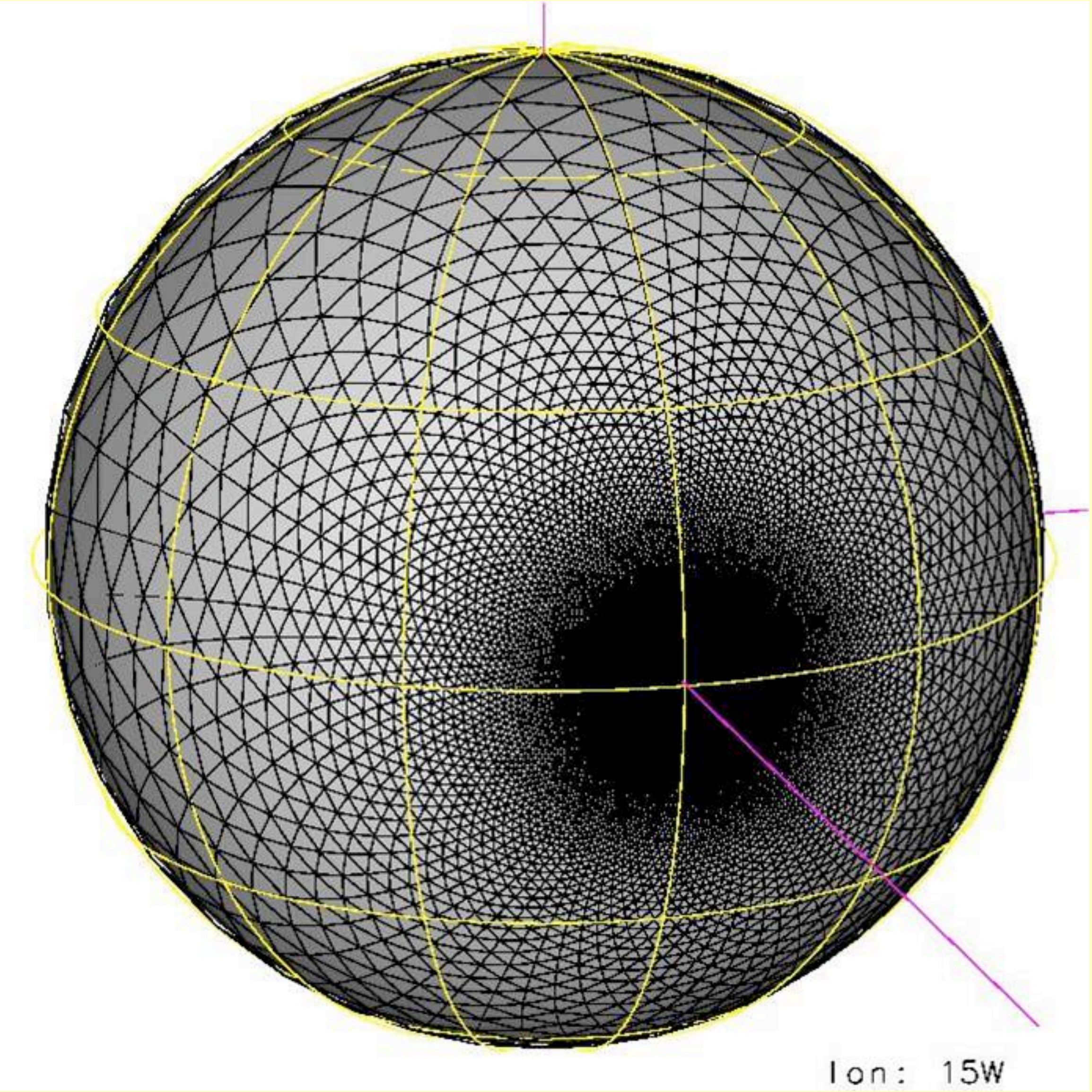


GEM
Canadian Model

Static Adaptations:
Rotated and transformed (Schmidt) lat-lon grid

Model Arpege
Meteo France

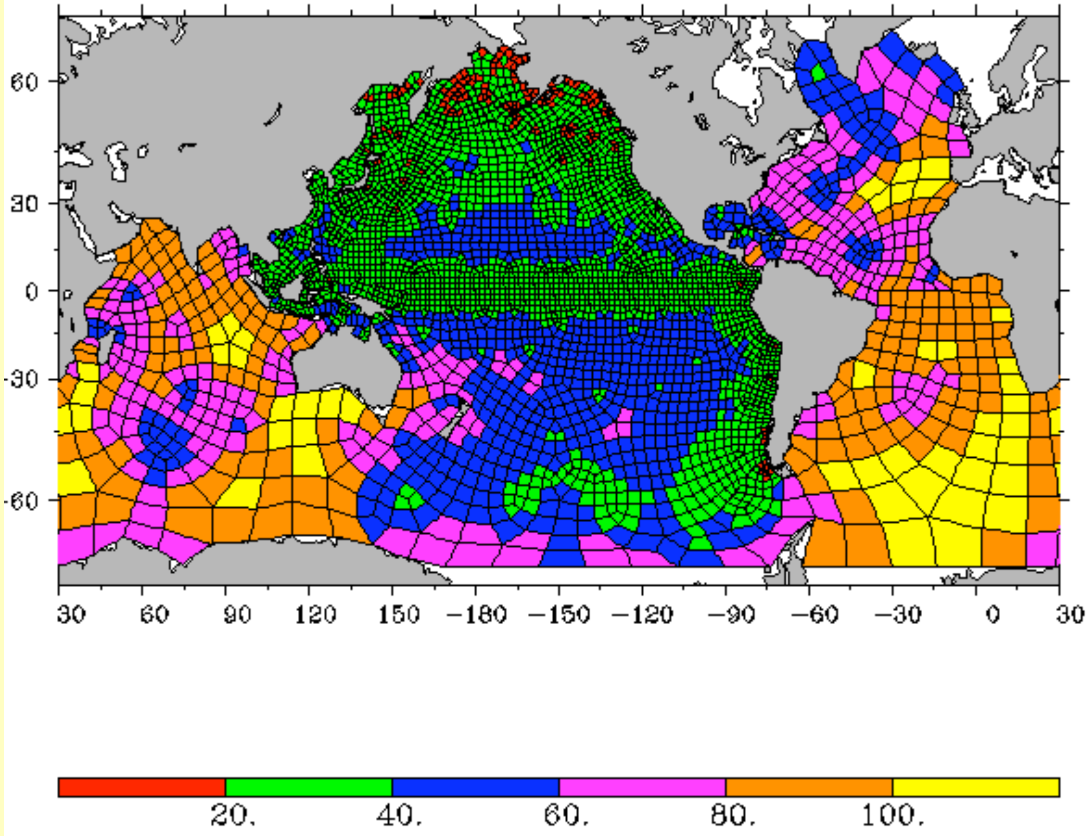
Static Adaptations: Stretched Icosahedral Grid (Schmidt transformation)



Courtesy of
H. Tomita
(Frontier Research System
for Global Change, Japan)

Static Adaptations: Unstructured Grids

Model SEOM: Spectral Element Ocean Model,
here 3552 elements with 64 collocation points



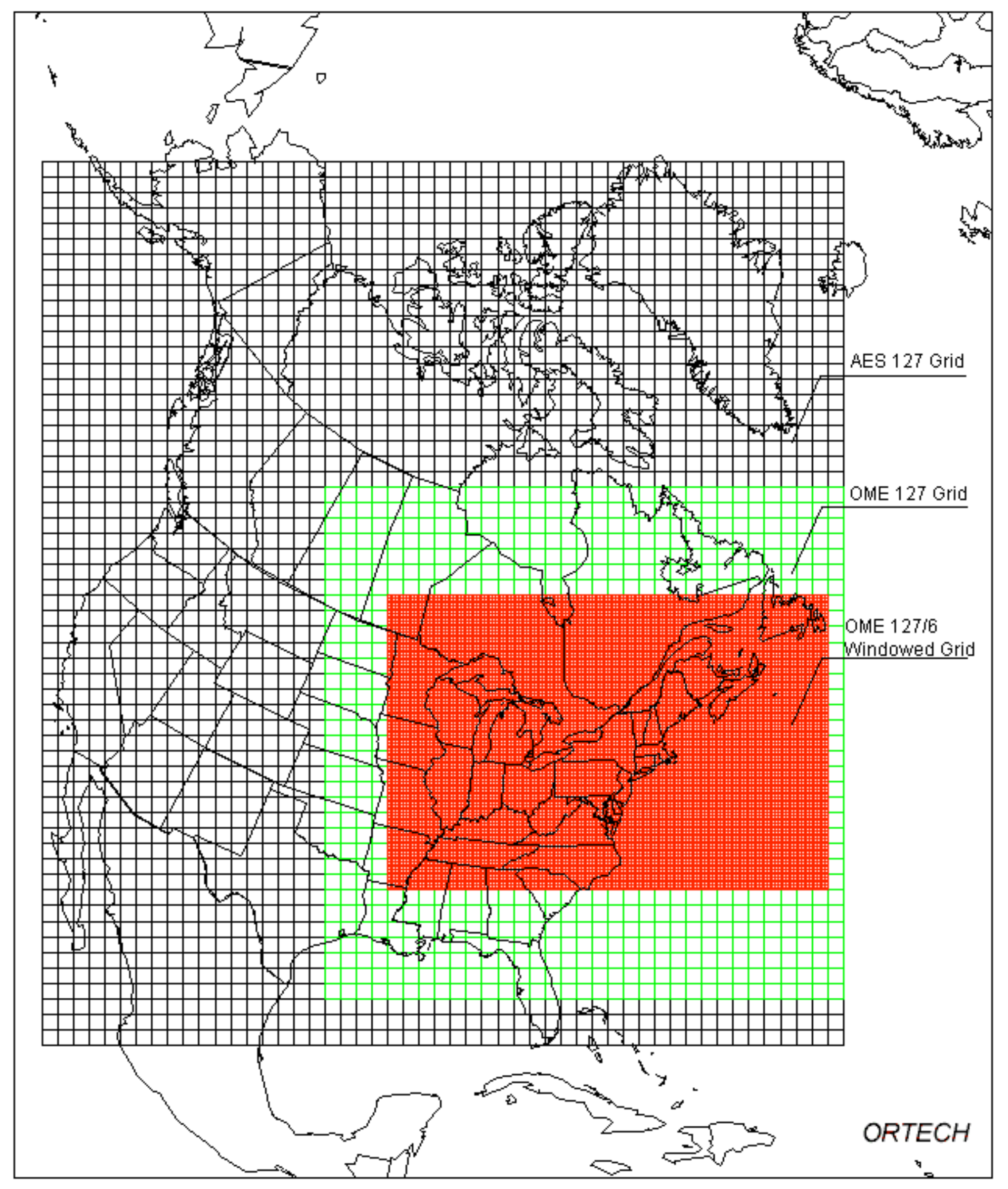
Average grid spacing (km) within each element

Spectral elements allow flexible configurations:

h and p refinements possible (compare to D.B. Haidvogel’s presentation)

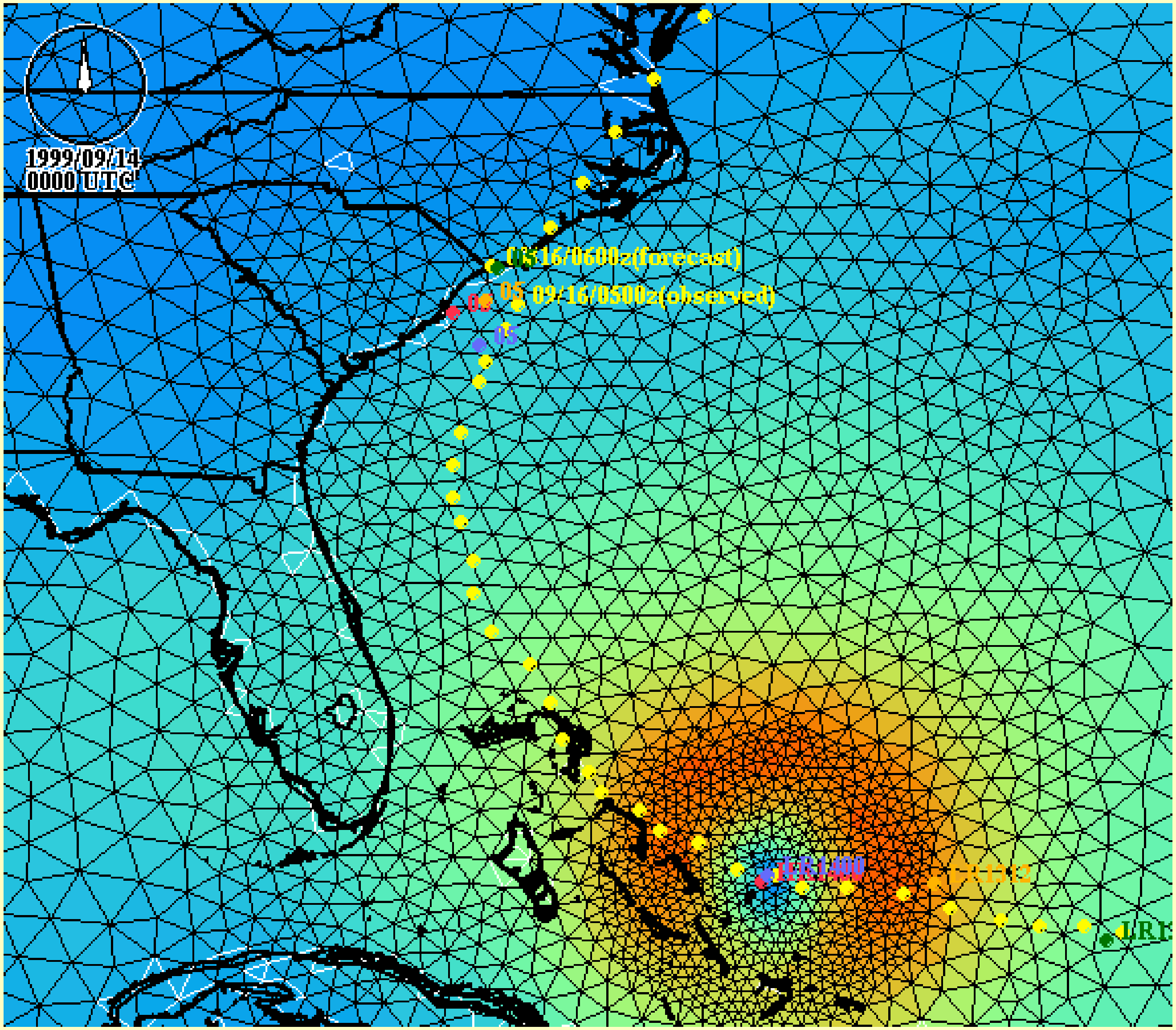
Source:
Rutgers University

Static adaptations: (Multiple) Nested Grids



Canadian Model

Dynamic Adaptations: Irregular Triangular Grid



Colors indicate the wind speed

Hurricane Floyd
(1999)

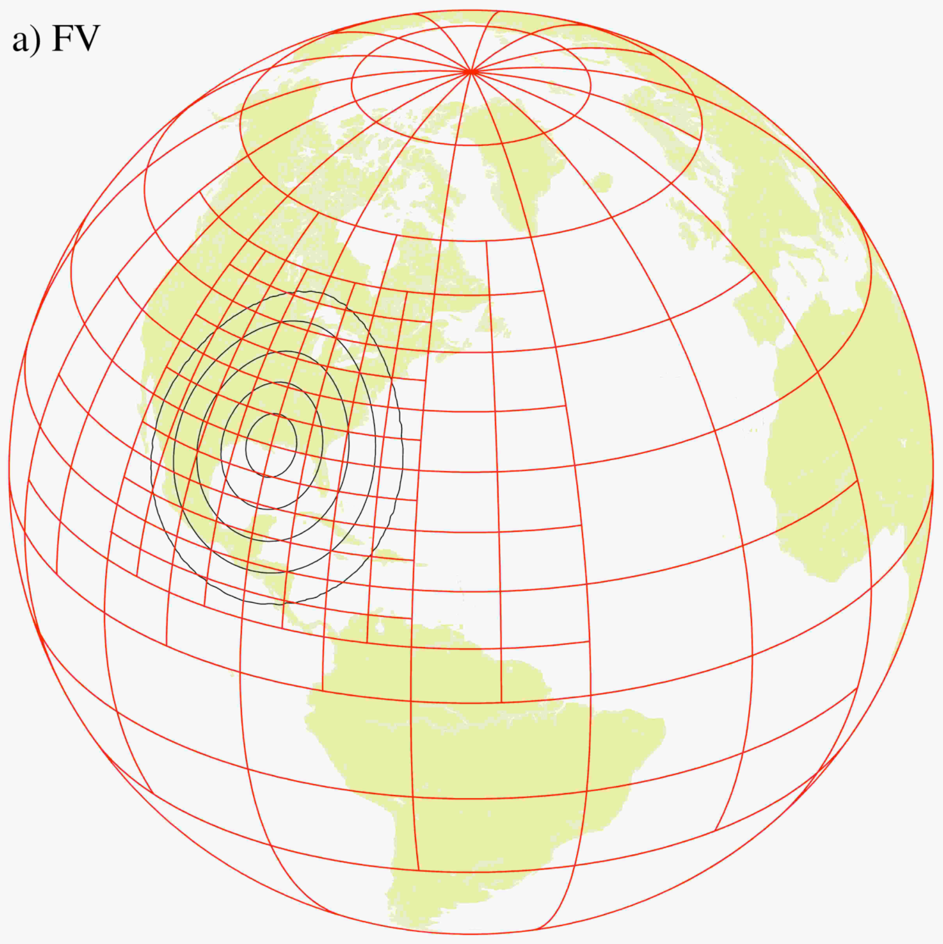
OMEGA model

Courtesy of
A. Sarma (SAIC, NC, USA)

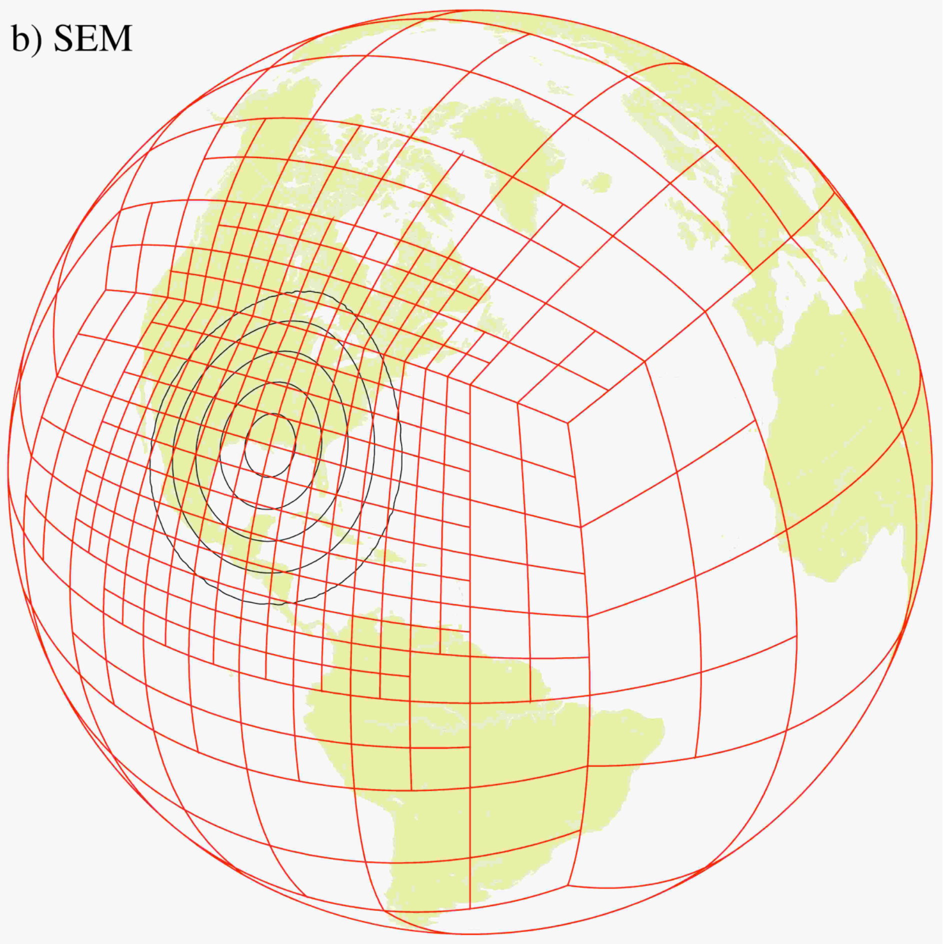
Two Adaptive Shallow Water Models

- AMR Comparison is based on a joint paper with Amik St-Cyr and collaborators from NCAR, MWR (2008)
- The AMR Spectral Element Model (SEM) was mainly developed by A. St-Cyr, J. Dennis & S. Thomas (NCAR), 2D shallow water (SW) version of the 3D dycore HOMME
- The AMR FV model is documented in Jablonowski (2004), Jablonowski et al. (2004, 2006)
- FV support by S.-J. Lin (GFDL)
- Contributors to the AMR FV model are R. Oehmke (NCAR), Q. Stout, J. Penner, B. van Leer, K. Powell (UM)

Adaptive Mesh Refinement (AMR): Latitude-Longitude Grid versus Cubed Sphere



Latitude-Longitude grid:
Model FV



Cubed-sphere grid:
Model SEM

Shallow Water Equations

Momentum equation in vector-invariant form

$$\frac{\partial \vec{v}_h}{\partial t} + (\zeta + f)\vec{k} \times \vec{v}_h + \vec{\nabla}(K - \nu D + g(h + h_s)) = 0$$

only in FV

Continuity equation

$$\frac{\partial h}{\partial t} + \vec{\nabla} \bullet \left(h\vec{v} \right) = 0$$

v_h horizontal velocity vector
ζ relative vorticity
f Coriolis parameter
$K = 0.5*(u^2 + v^2)$ kinetic energy
D horizontal divergence, ν damping coefficient
h depth of the fluid, h_s height of the orography
g gravitational acceleration

Finite Volume (FV) Shallow Water Model

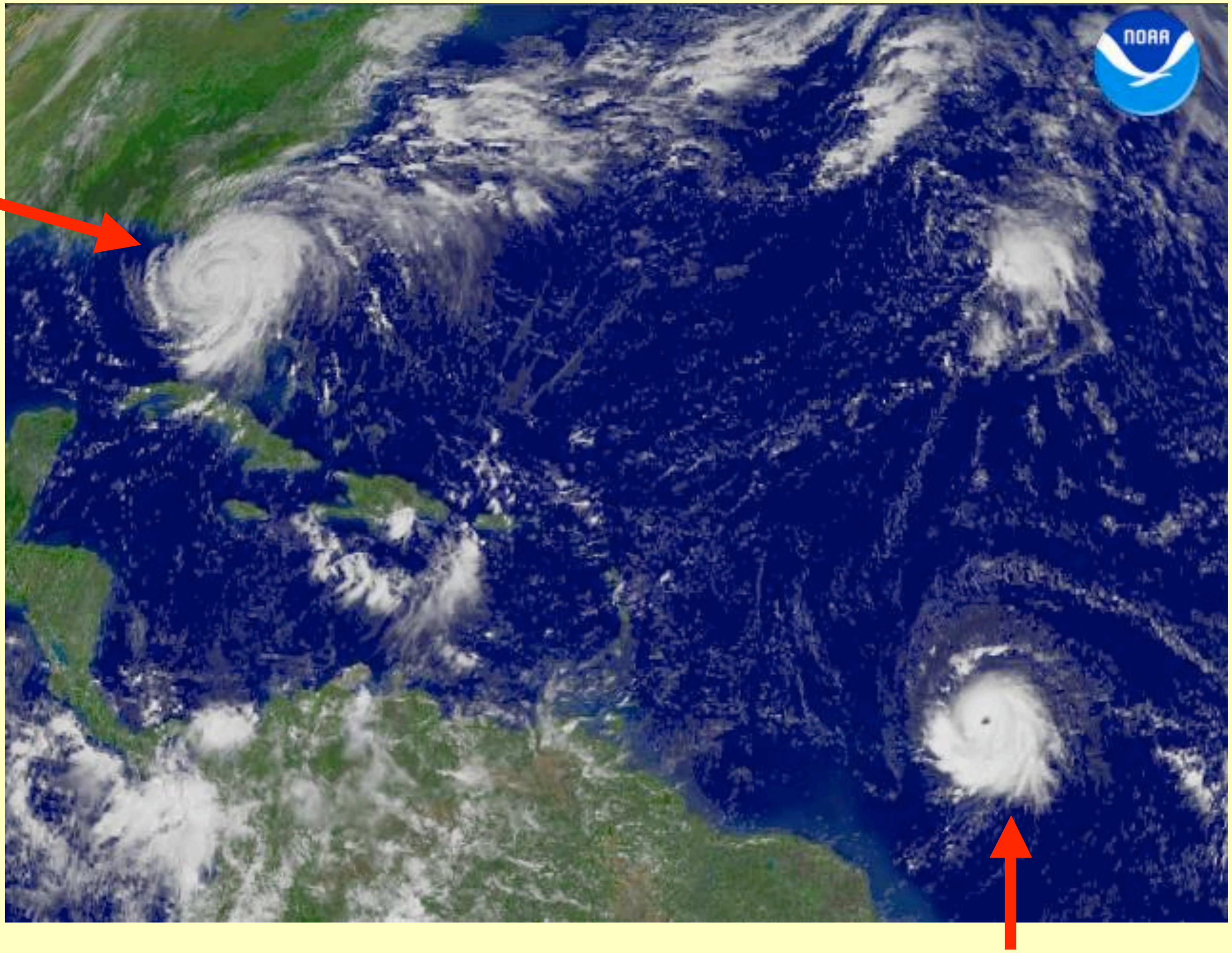
- Developed by Lin and Rood (1996), Lin and Rood (1997)
  - 3D version available (Lin 2004), built upon the SW model:
    - hydrostatic dynamical core used for climate and weather predictions
    - ⇨ Currently part of NCAR’s, NASA’s and GFDL’s General Circulation Models

- **Numerics:** Finite volume approach
  - conservative and monotonic transport scheme
  - van Leer second order scheme for time-averaged numerical fluxes
  - PPM third order scheme (Piecewise Parabolic Method) for prognostic variables
  - Staggered grid (Arakawa D-grid), C-grid for mid-time levels
  - Orthogonal Latitude-Longitude computational grid

Spectral Element (SEM) Shallow Water Model

- Documented in Thomas and Loft (2002), St-Cyr and Thomas (2005), St-Cyr et al. (2007)
  - 3D version available (no 3D AMR version though)
  - 3D hydrostatic dynamical core is part of NCAR's CAM model (model HOMME)
- **Numerics:** Spectral Elements
  - Non-conservative (no longer as we learned from Mark and Aimé) and non-monotonic (still true)
  - Allows high-order numerical method
  - Spectral convergence for smooth flows
  - GLL and GL collocation points
  - Non-orthogonal cubed-sphere computational grid

Features of Interest in a Multi-Scale Regime



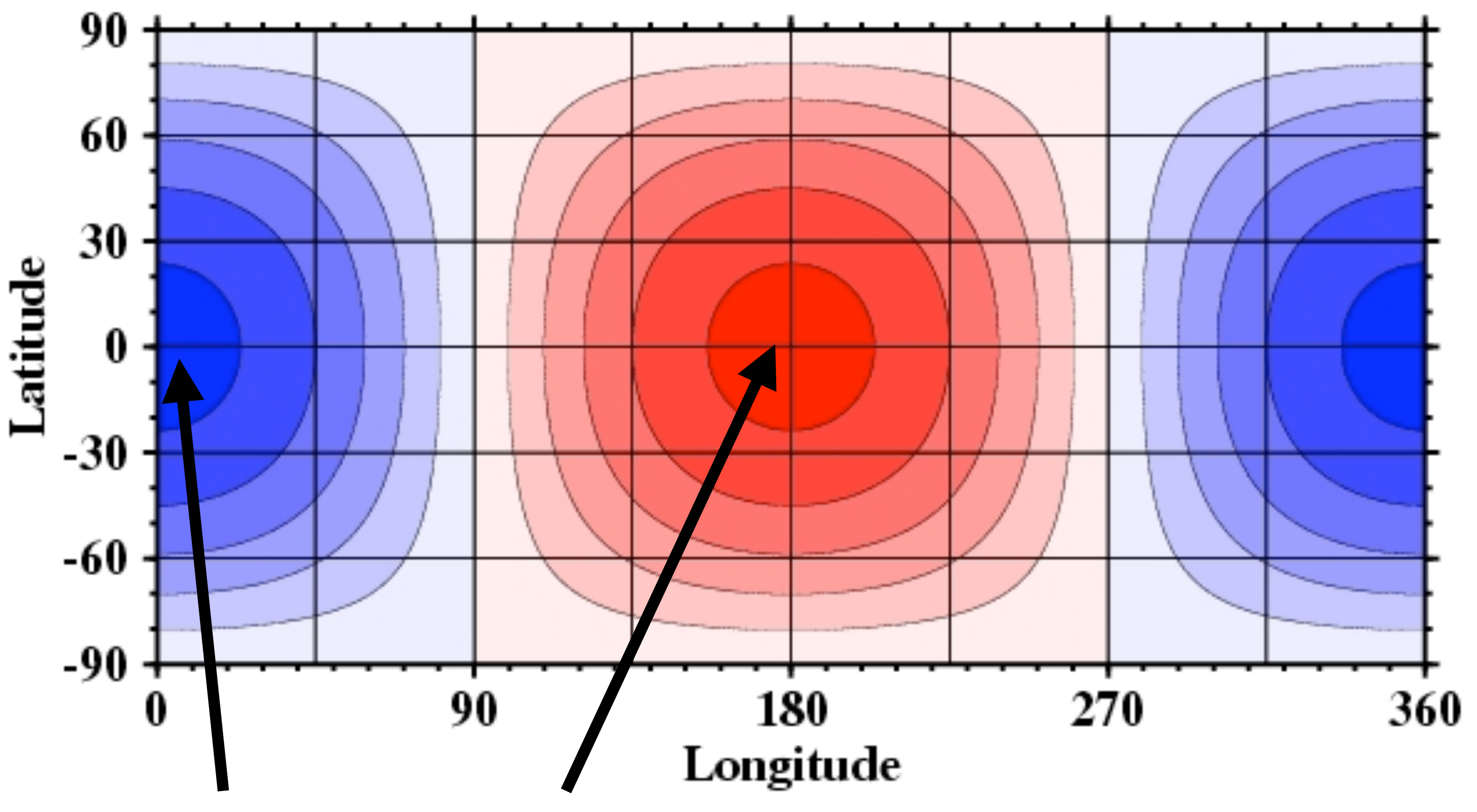
Hurricane Frances

Hurricane Ivan

September/5/2004

Idealized assessment of cyclones in SW models

Combines solid body rotation and idealized cyclogenesis test case

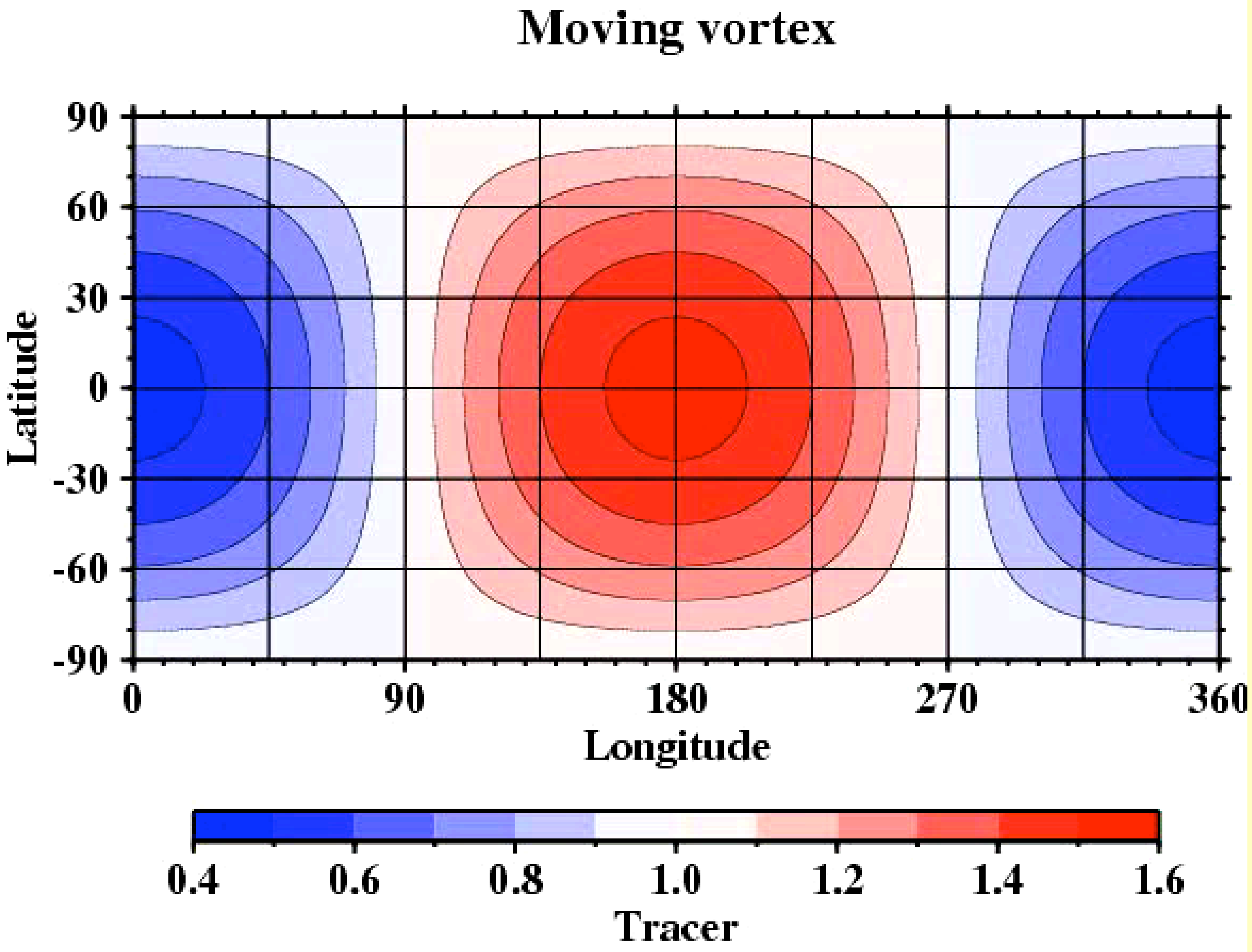


'Hurricane Frances'

'Hurricane Ivan'

Nair and Jablonowski, MWR, 2008

Idealized assessment of cyclones in SW models



FV SW model, 5ºx5º initial resolution

2 dynamic refinement levels 1.25ºx1.25º

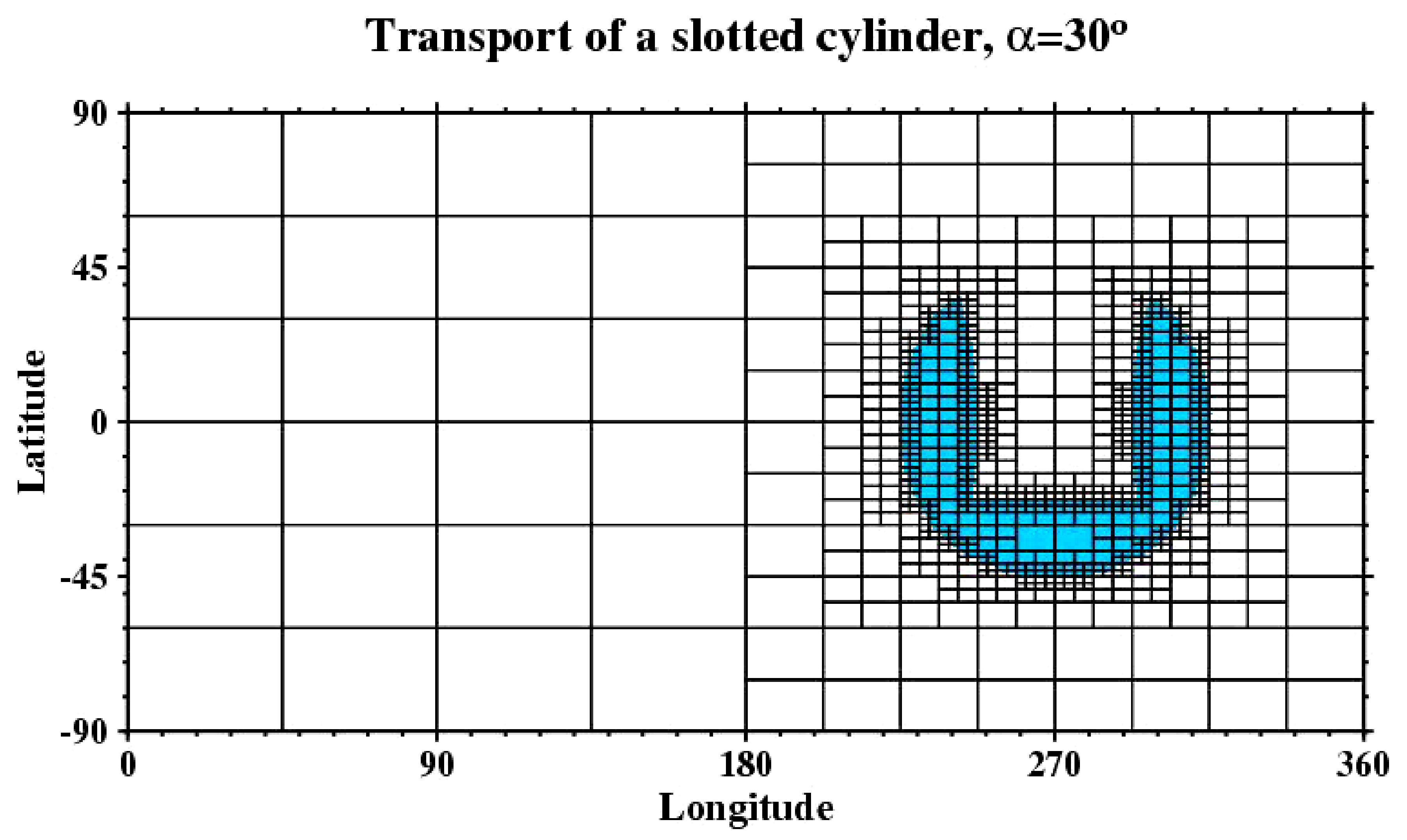
dynamic ref. criterion: gradient

12-day simulation

Overview of the AMR comparison

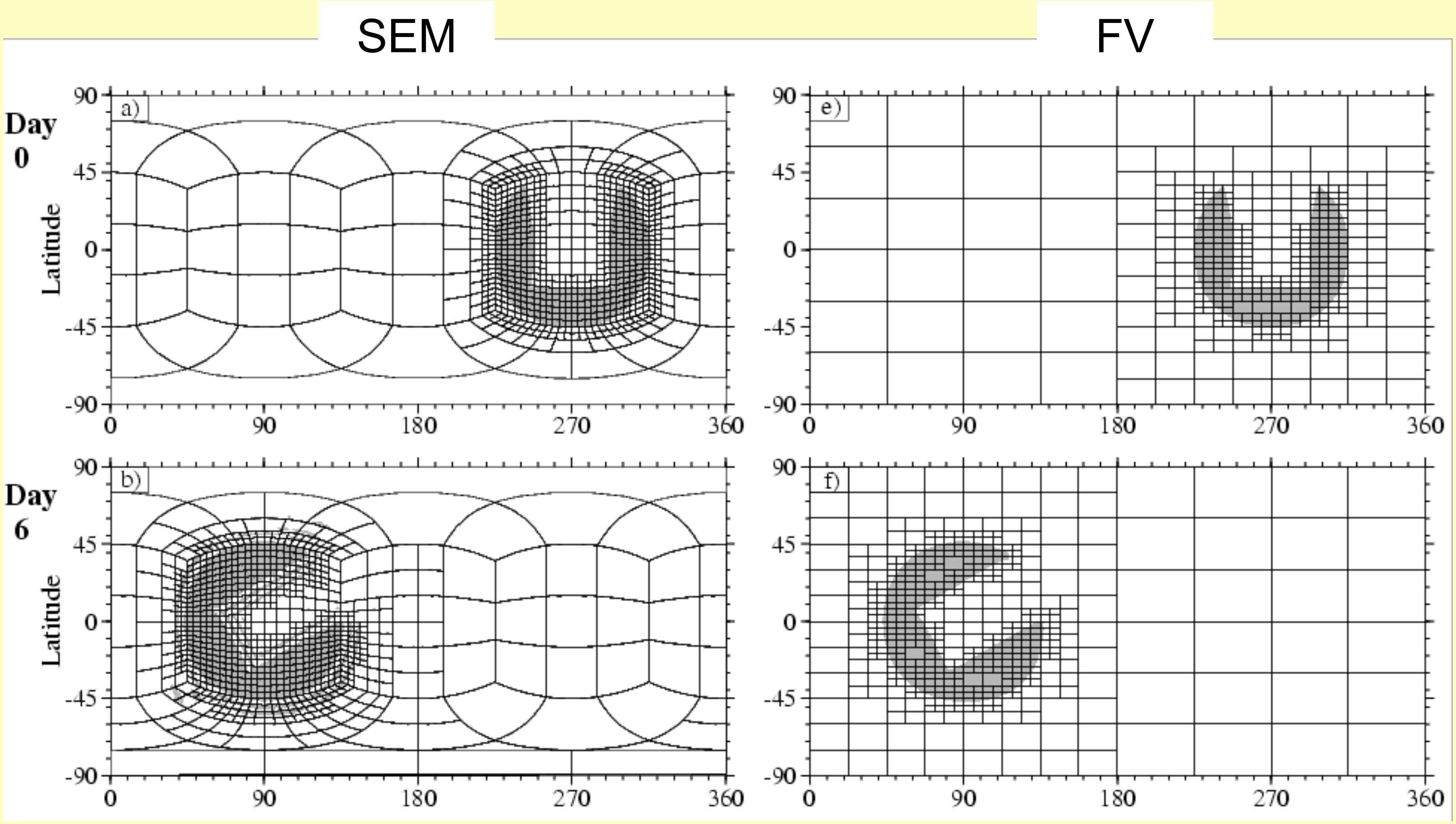
- 2D shallow water tests: Williamson et al. (1992) + extensions of the shallow water test suite
  - Dynamic refinements for pure advection
    - Slotted cylinder
    - Cosine bell advection test
  - Dynamic refinements and refinement criteria: Flow over a mountain
- Barotropic instability test (Galewsky et al., Tellus 2004)
- 3D Baroclinic waves (Jablonowski and Williamson, QJRMS (2006) & NCAR Technical Report (2006))

AMR Transport of a Slotted Cylinder



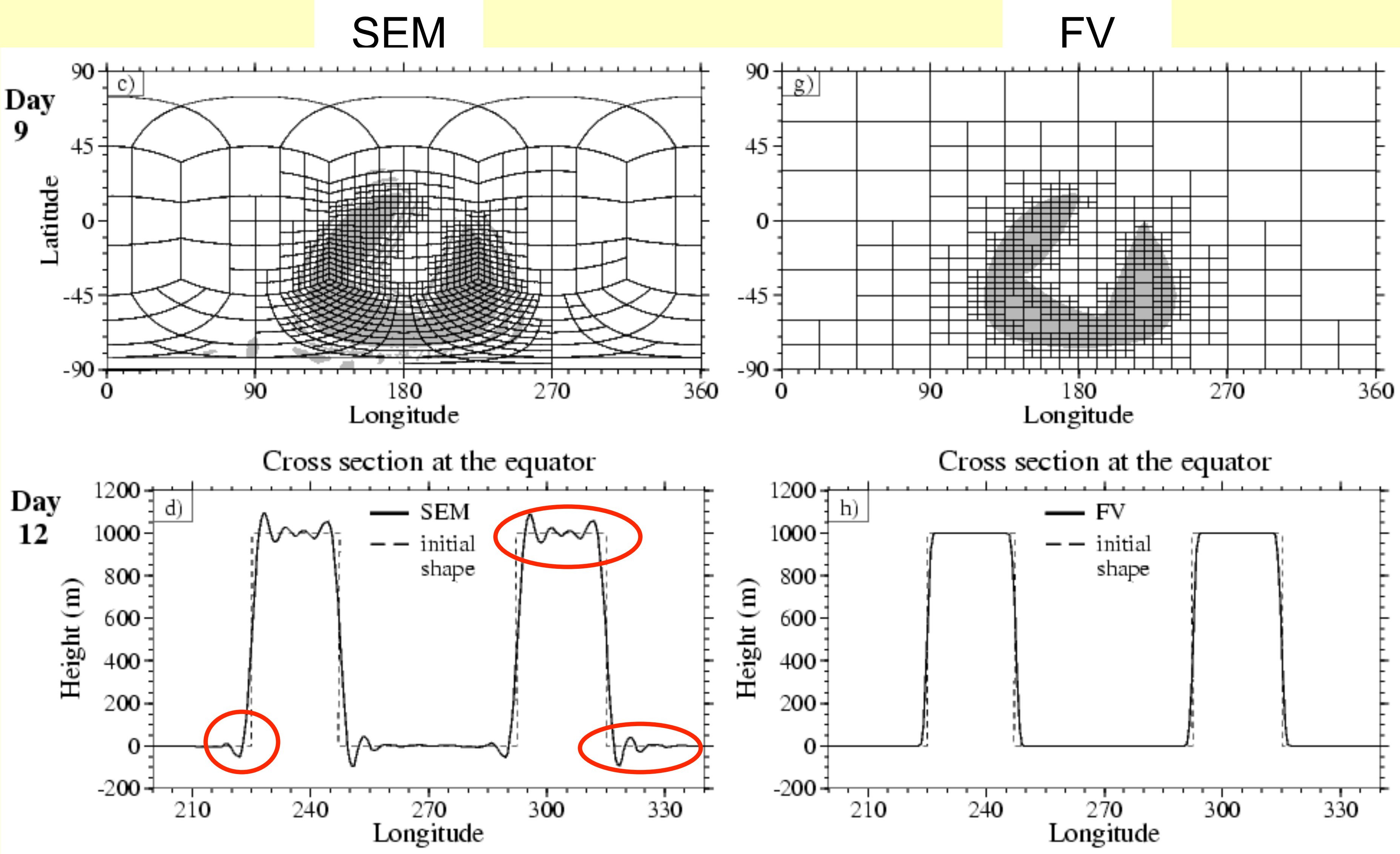
Model FV

Transport of a Slotted Cylinder



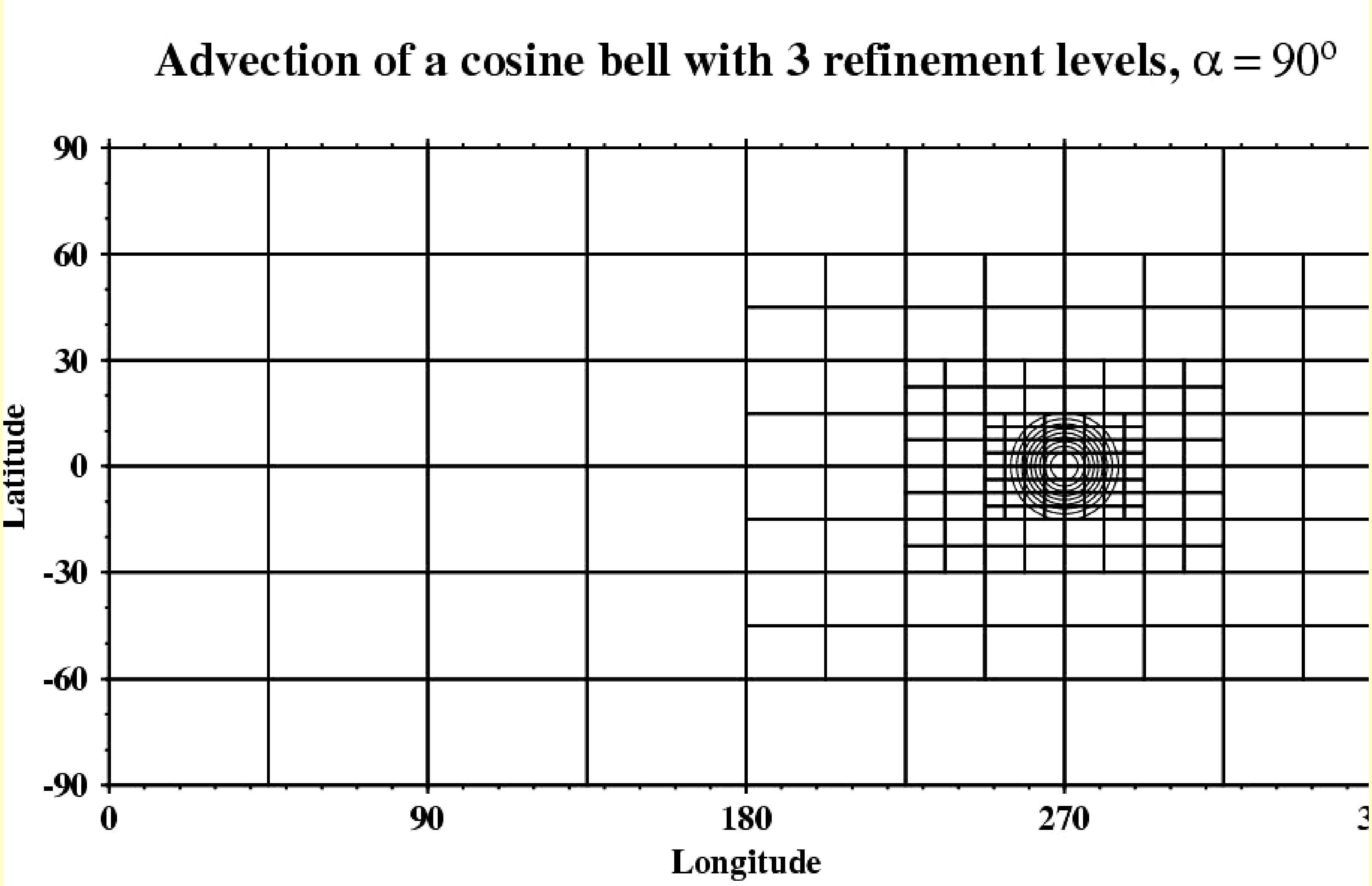
5 x 5 deg base grid, 3 refinement levels

Transport of a Slotted Cylinder



- Slotted cylinder is reliably detected and tracked
- Over- and undershoots in SEM, FV monotonic

Advection of a Cosine Bell with α = 90°

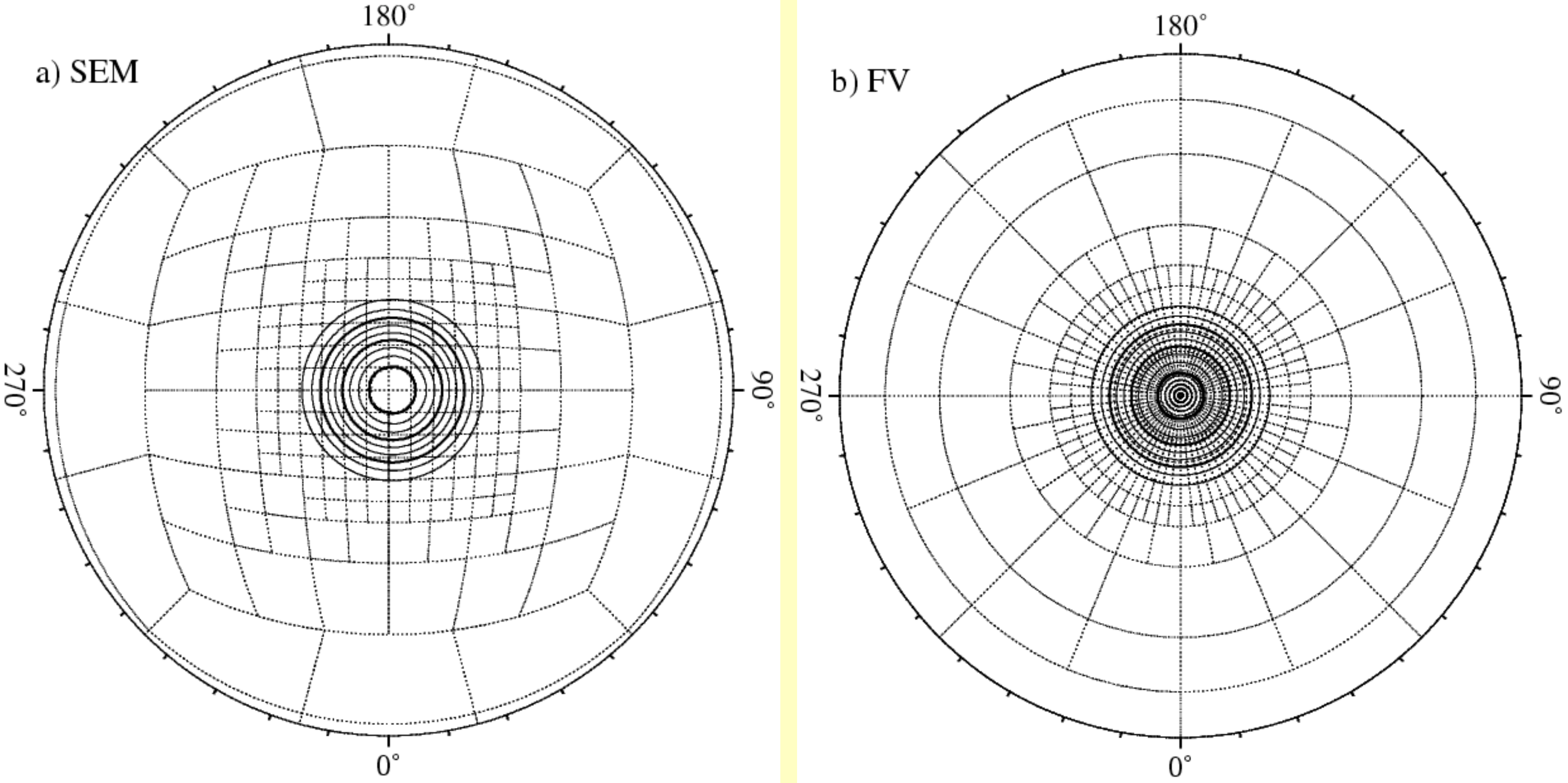


Advection of a cosine bell with 3 refinement levels, $\alpha = 90^{\circ}$

Model FV

Snapshots: Cosine Bell at day 3

North-polar stereographic projection at day 3 for α = 90

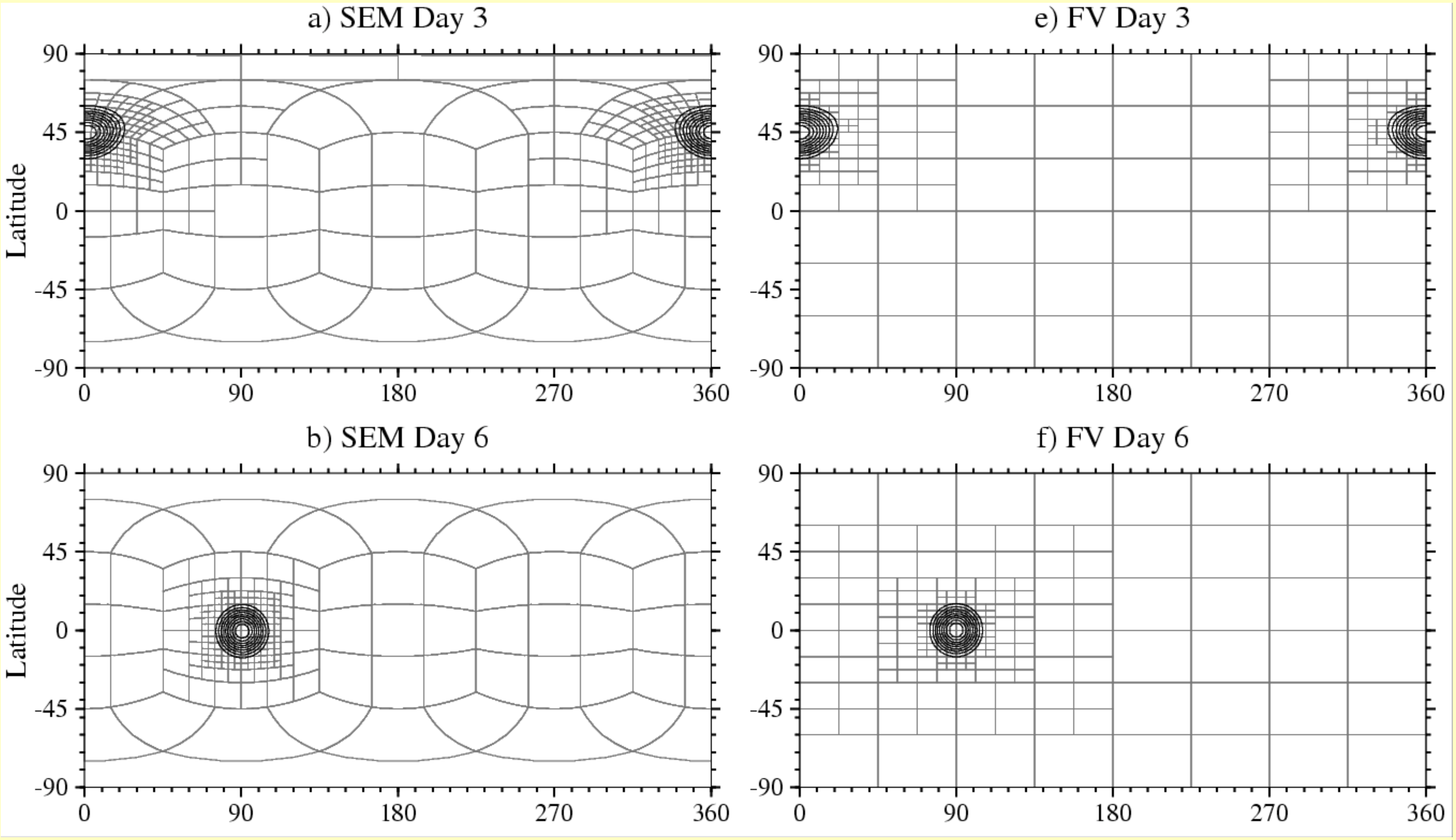


Uniform distribution in SEM, Convergence of blocks in FV

Snapshots: Advection of a Cosine Bell

SEM

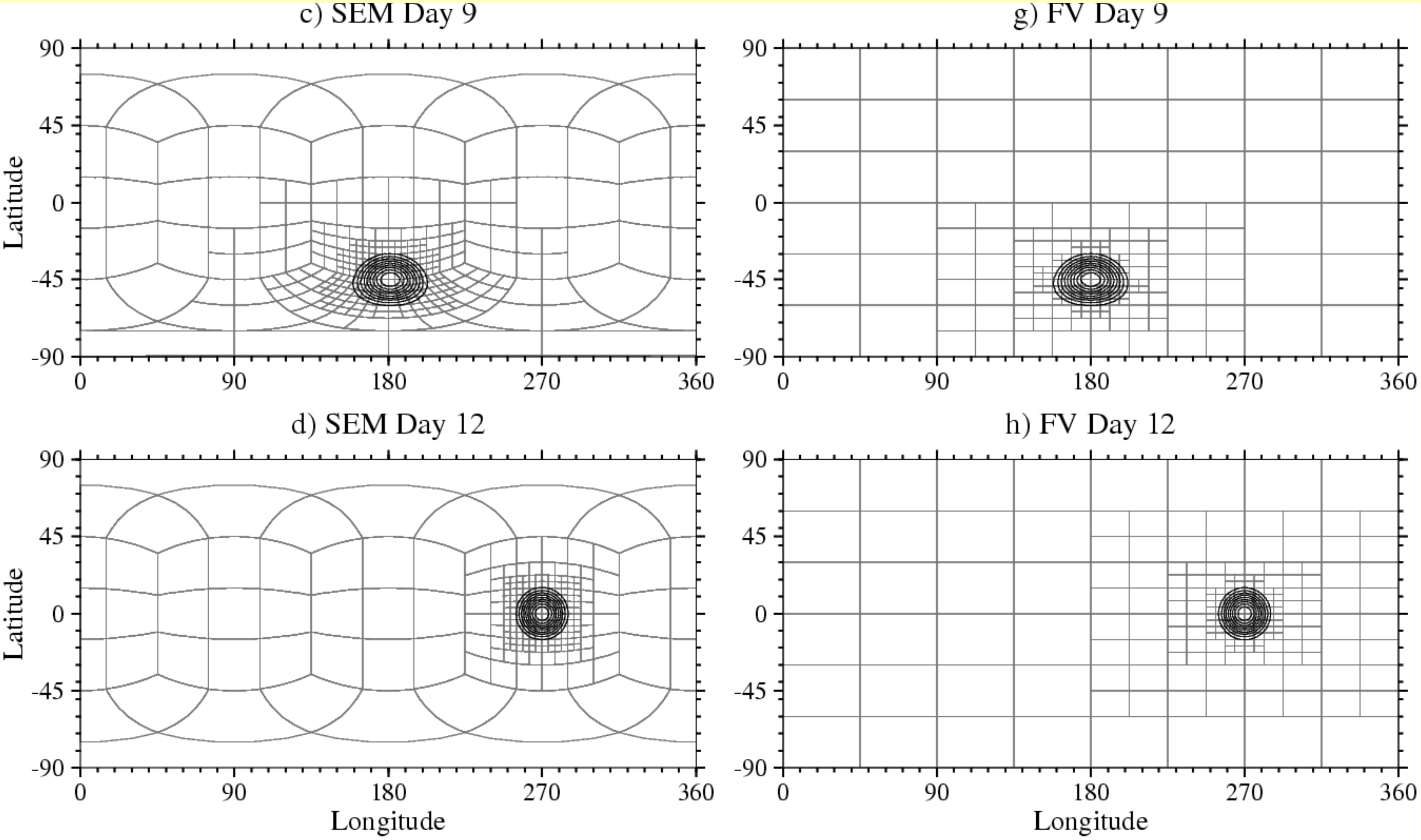
FV



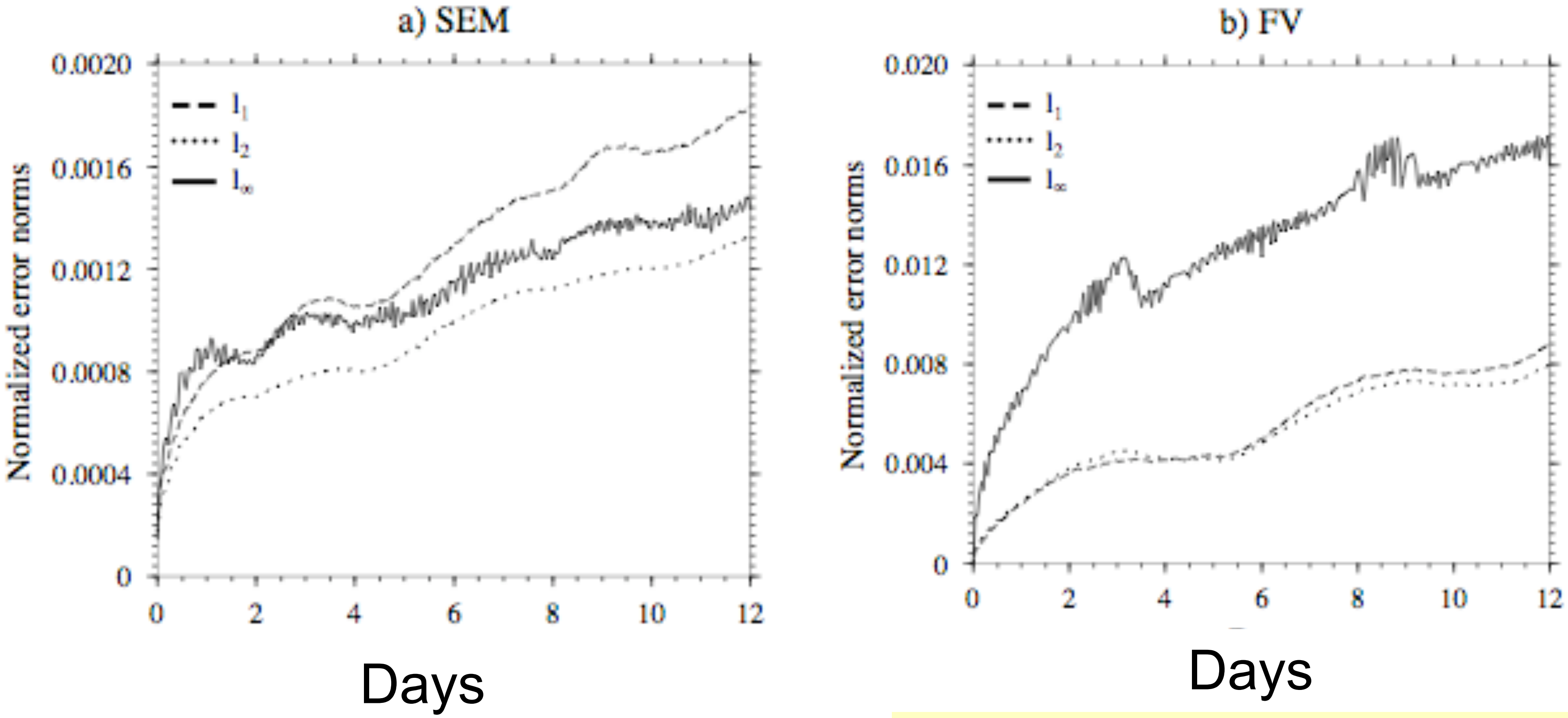
Snapshots: Advection of a Cosine Bell

SEM

FV



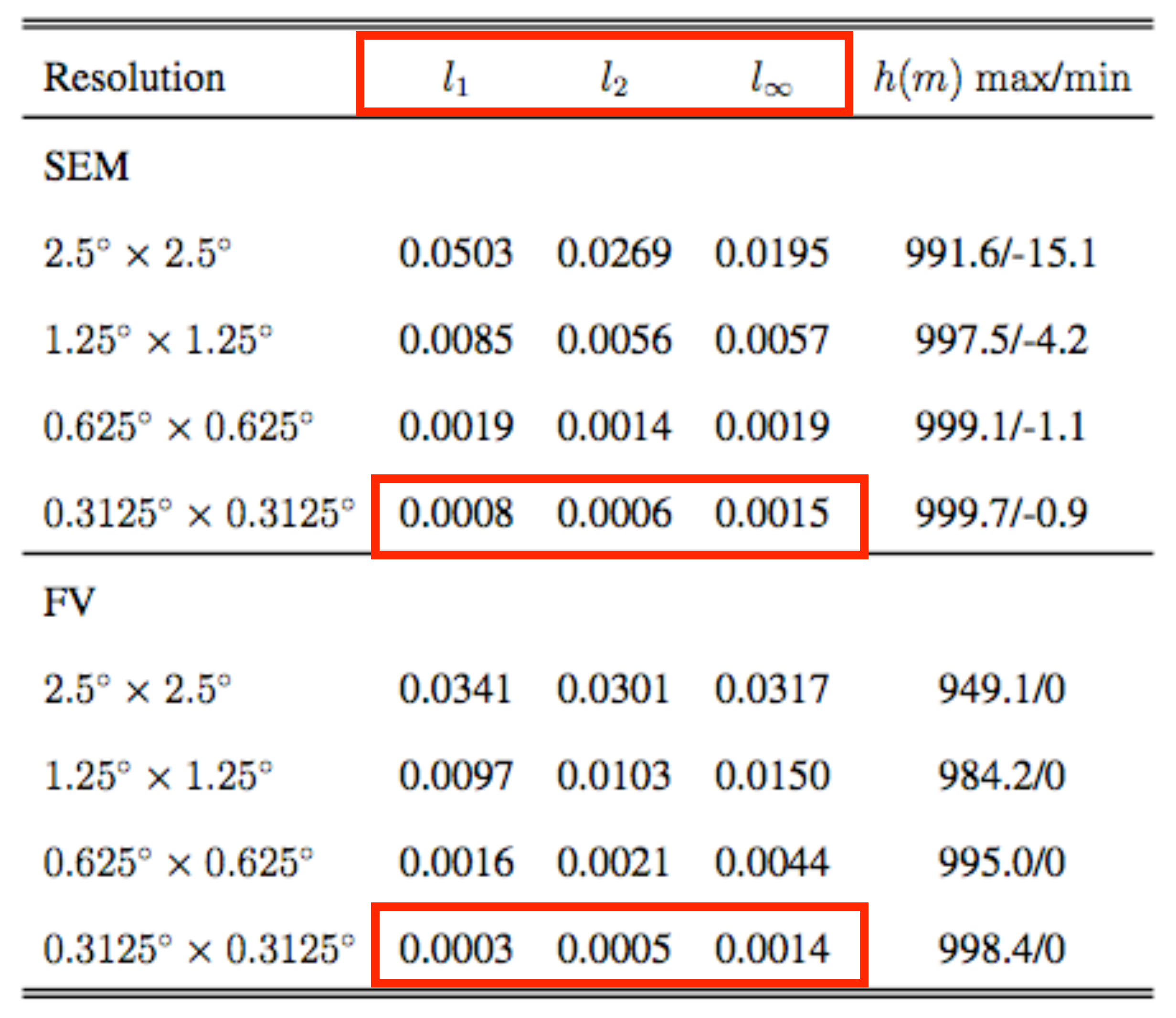
Error norms: Cosine Bell Advection



Rotation angle α= 45:

Errors in SEM are lower than errors in FV

Error norms after 12 days



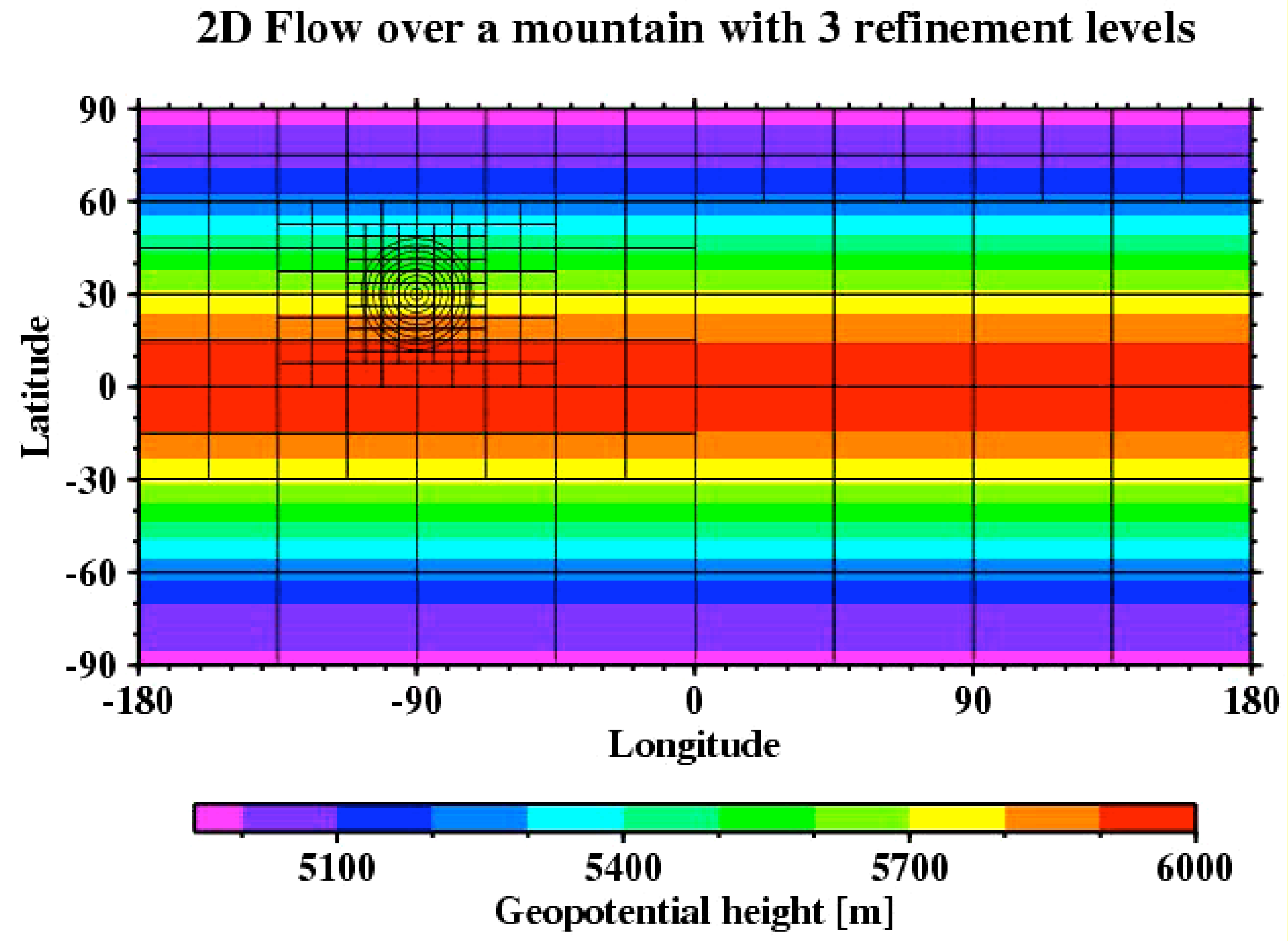
Resolution	l_1	l_2	l_∞	$h(m)$ max/min
SEM				
2.5° × 2.5°	0.0503	0.0269	0.0195	991.6/-15.1
1.25° × 1.25°	0.0085	0.0056	0.0057	997.5/-4.2
0.625° × 0.625°	0.0019	0.0014	0.0019	999.1/-1.1
0.3125° × 0.3125°	0.0008	0.0006	0.0015	999.7/-0.9
FV				
2.5° × 2.5°	0.0341	0.0301	0.0317	949.1/0
1.25° × 1.25°	0.0097	0.0103	0.0150	984.2/0
0.625° × 0.625°	0.0016	0.0021	0.0044	995.0/0
0.3125° × 0.3125°	0.0003	0.0005	0.0014	998.4/0

Rotation angle $\alpha = 0$

SEM produces undershoots

Errors for $\alpha = 0$ are comparable

2D Dynamic adaptations in FV

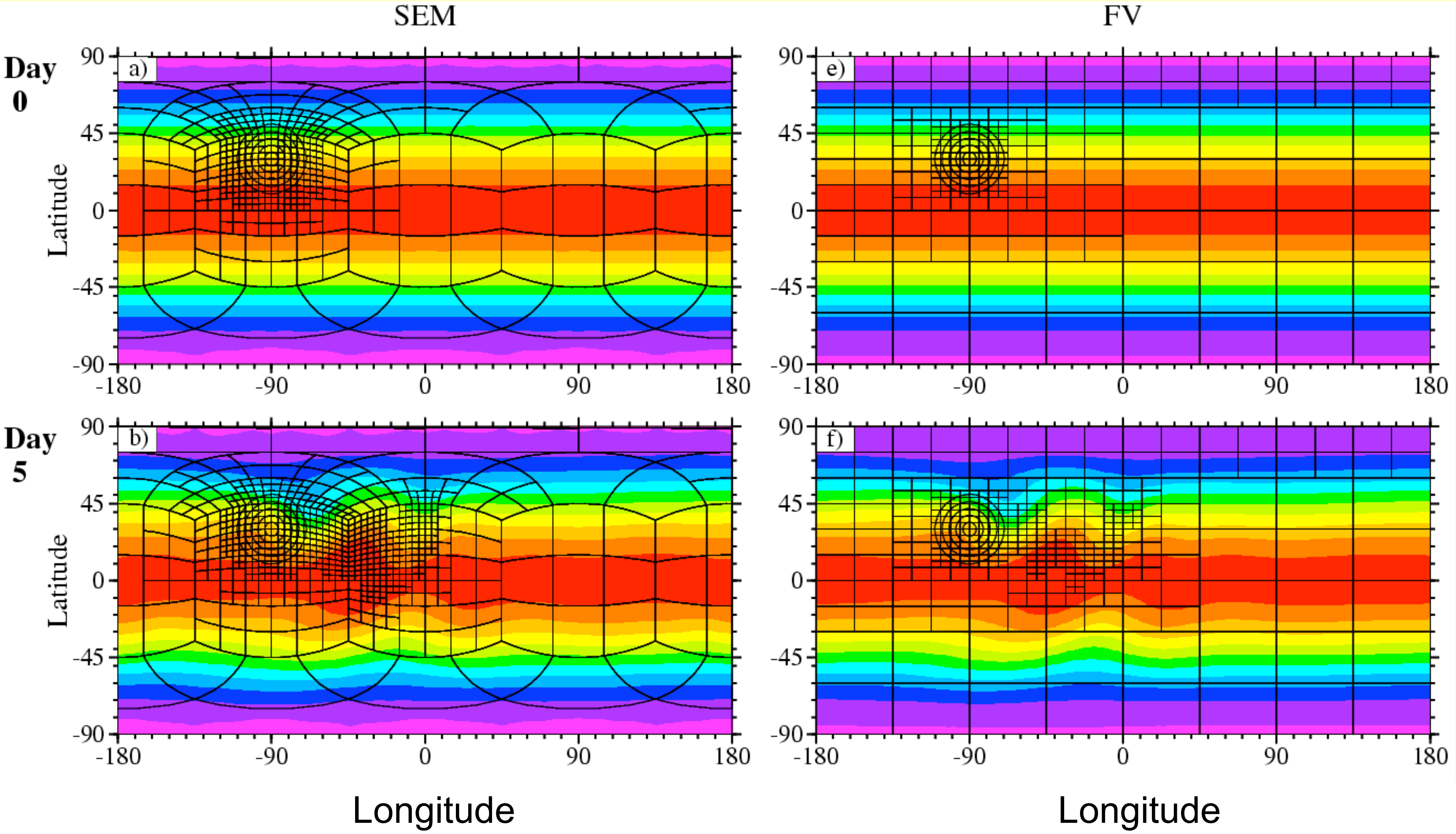


Vorticity-based adaptation criterion

2D shallow water test #5: 15-day run

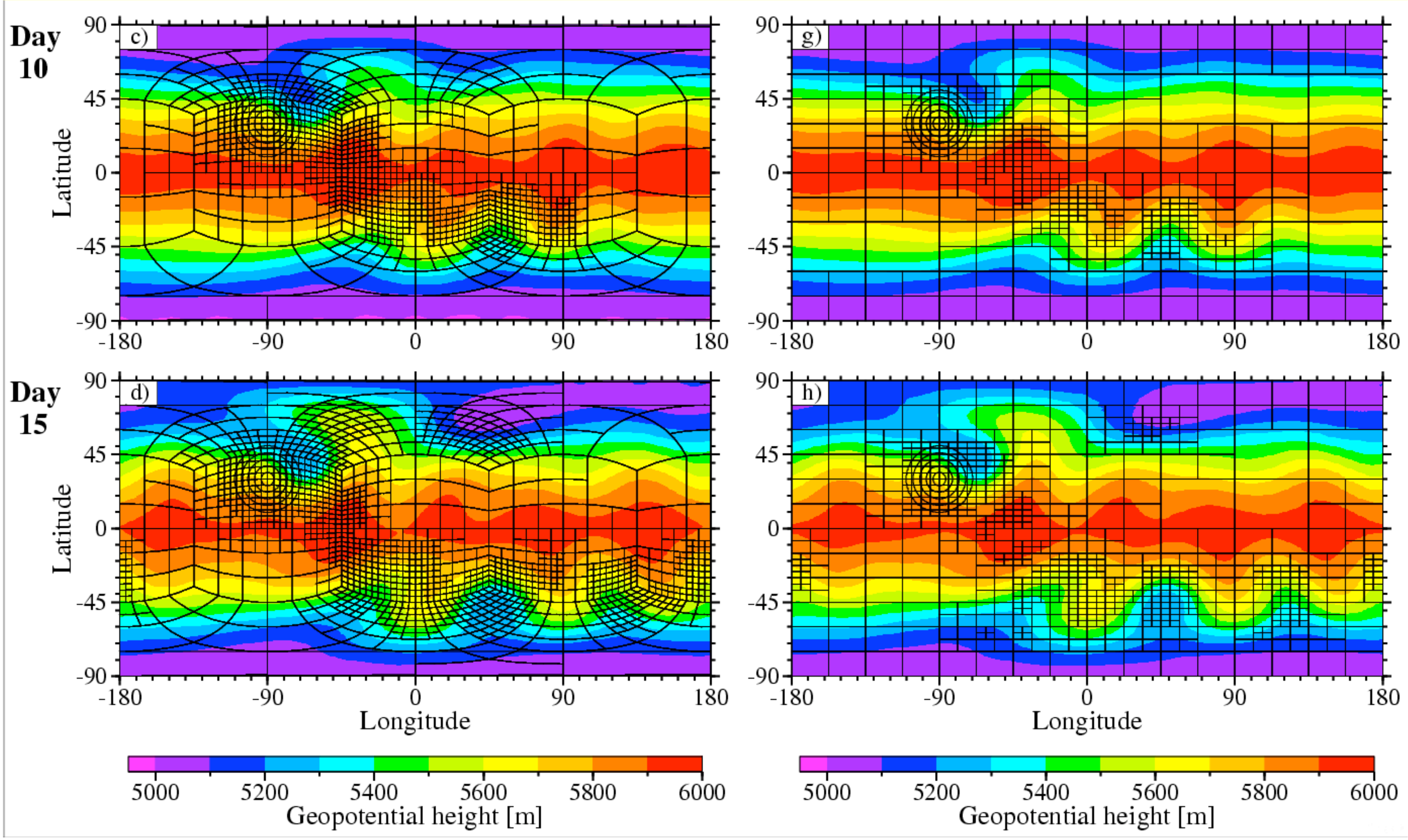
Snapshots: Flow over a mountain

Geopotential height field (SW test case 5)

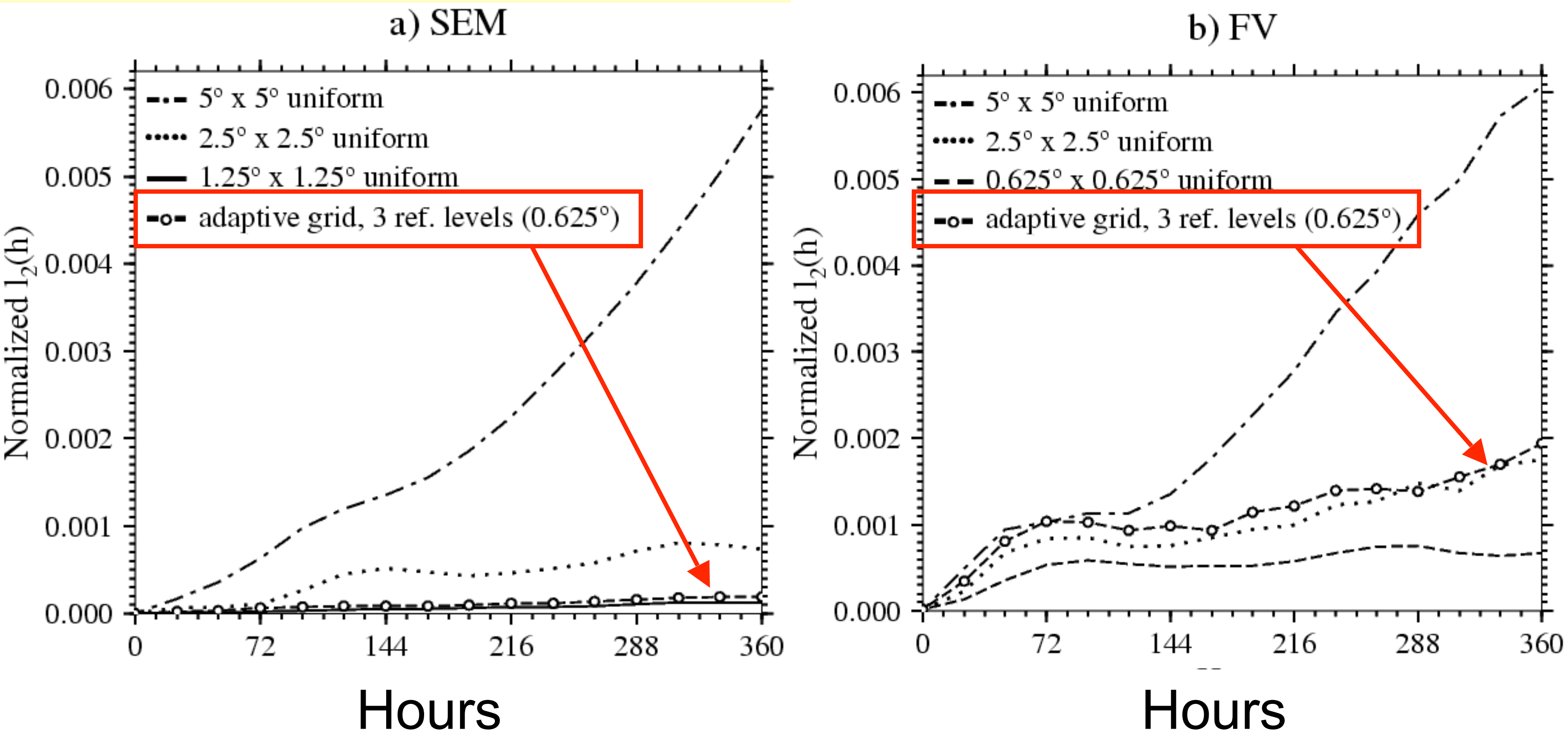


Snapshots: Flow over a mountain

Geopotential height field (SW test case 5)



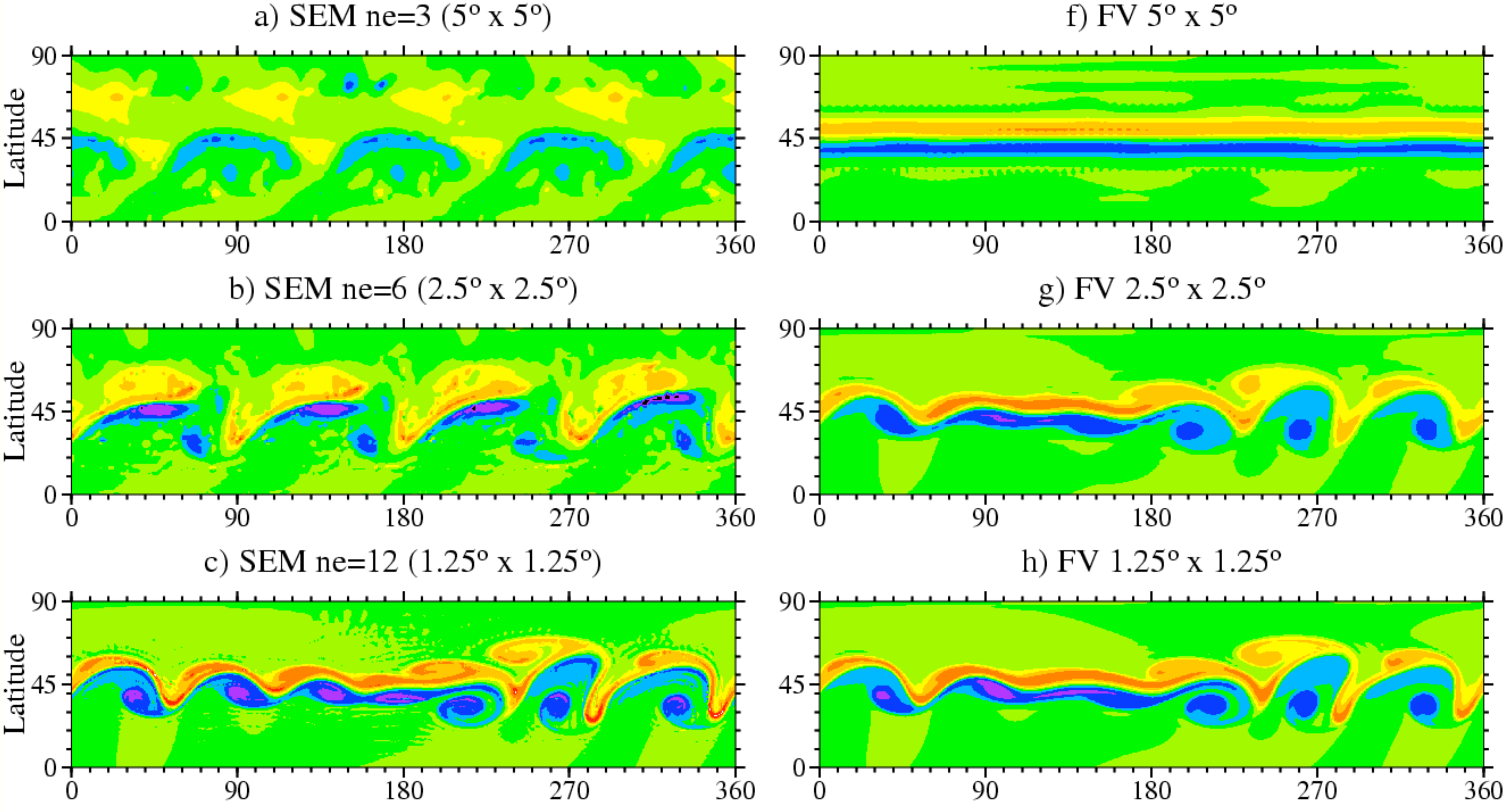
Error norms: Test case 5



Errors in SEM converge quicker to the reference solution (T426 NCAR spectral model, provided by DWD)

Barotropic instability test case

Convergence analysis: Relative vorticity at day 6


a) SEM ne=3 (5° x 5°)

f) FV 5° x 5°

b) SEM ne=6 (2.5° x 2.5°)

g) FV 2.5° x 2.5°

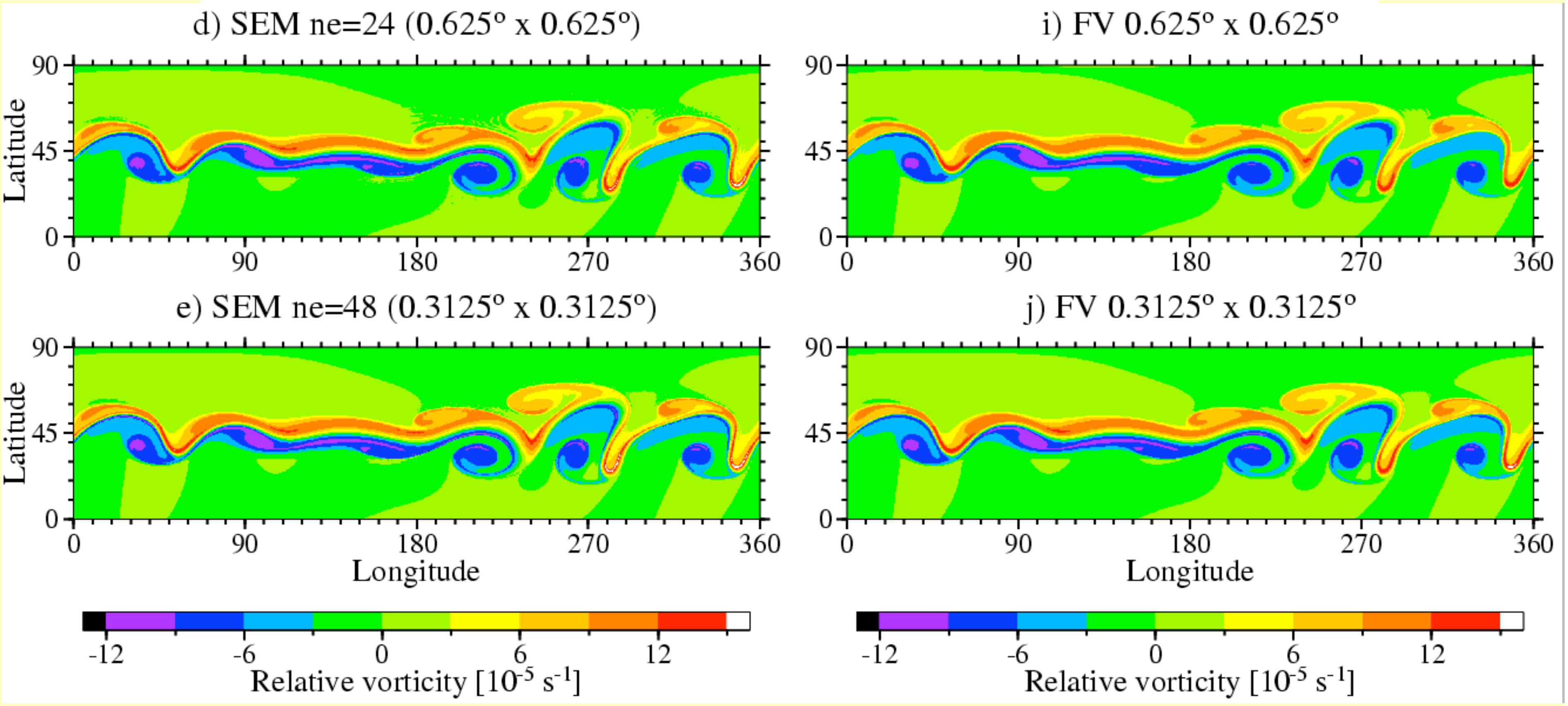
c) SEM ne=12 (1.25° x 1.25°)

h) FV 1.25° x 1.25°

1.25° resolution is needed to get a good representation of the wave

Barotropic instability test case: 'Reference Solution'

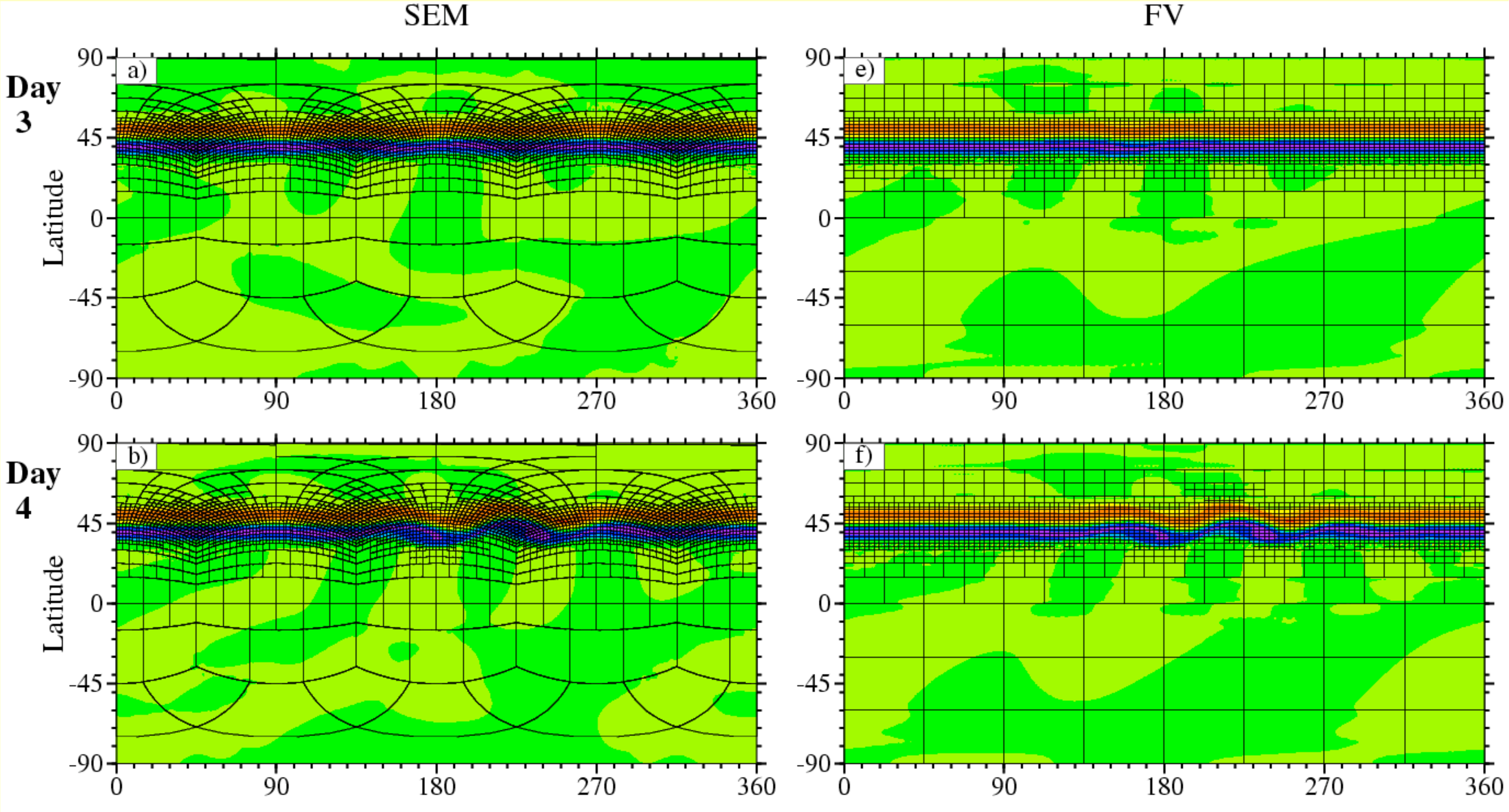
Convergence analysis: Relative vorticity at day 6



Second highest and highest resolutions are very similar to each other, SEM and FV are similar

Barotropic instability test case

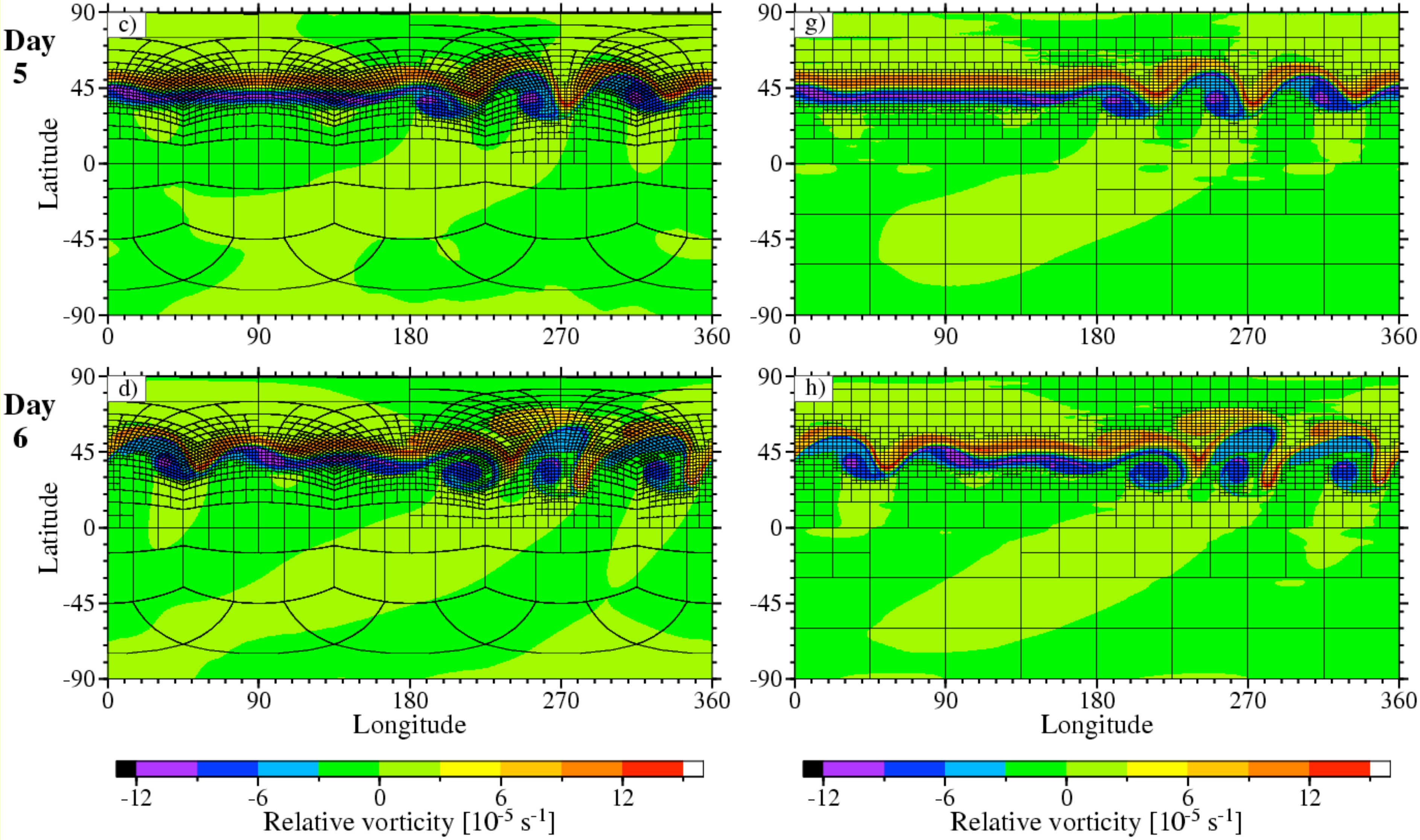
Vorticity-based adaptation criterion: Day 3 and 4



5 deg base grid, 4 refinement levels

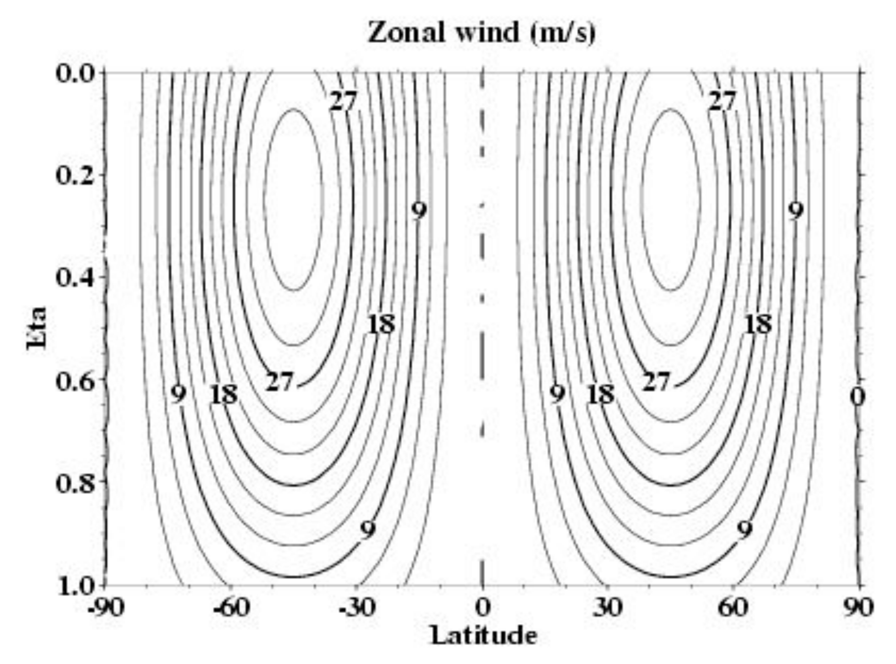
Barotropic instability test case

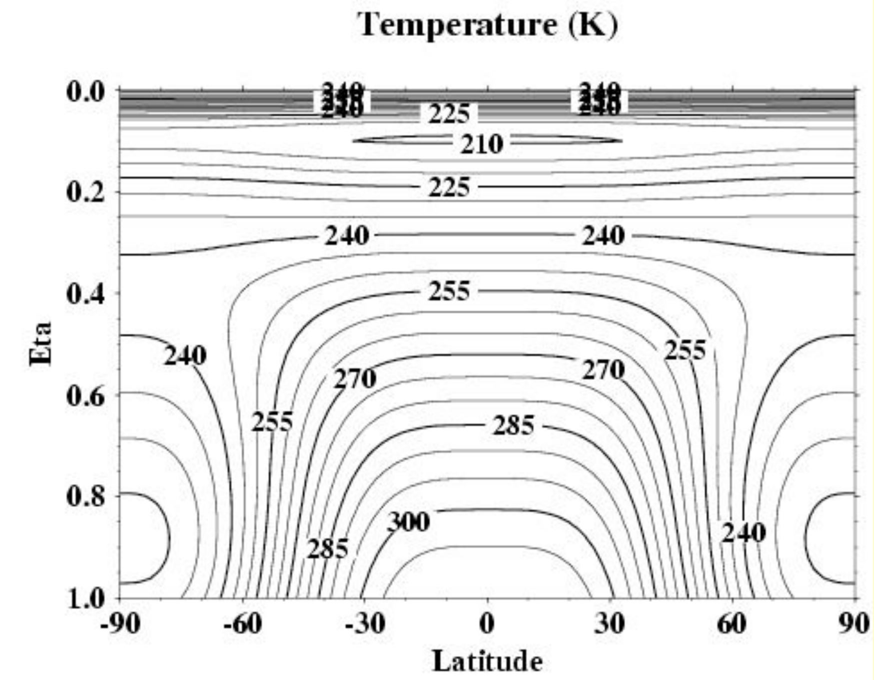
AMR Grids and solutions in SEM and FV are very similar



3D Baroclinic wave test case

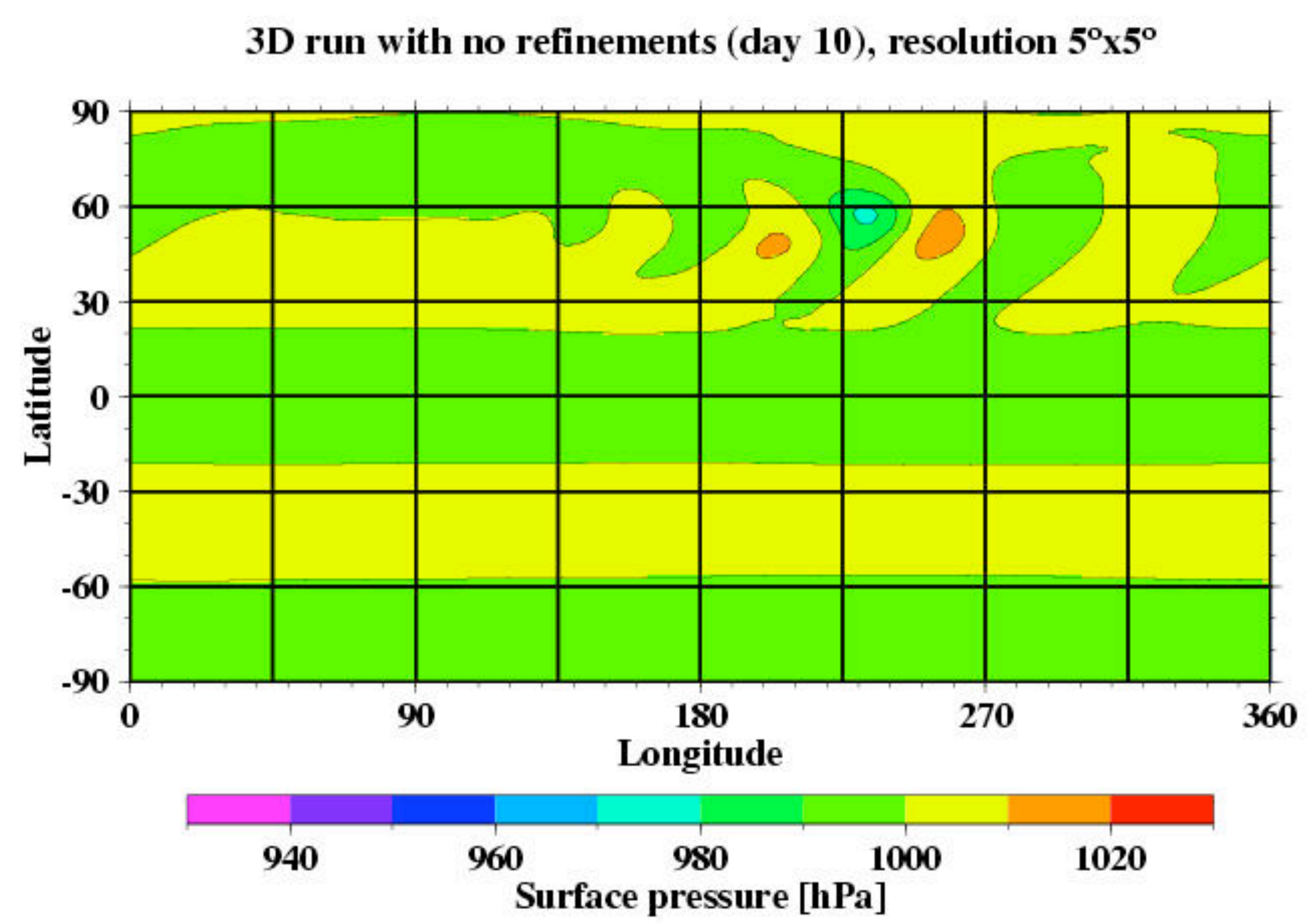
- analytically specified balanced initial field with overlaid perturbation
- baroclinic wave develops after 5-10 days
- deterministic test that converges towards reference solution





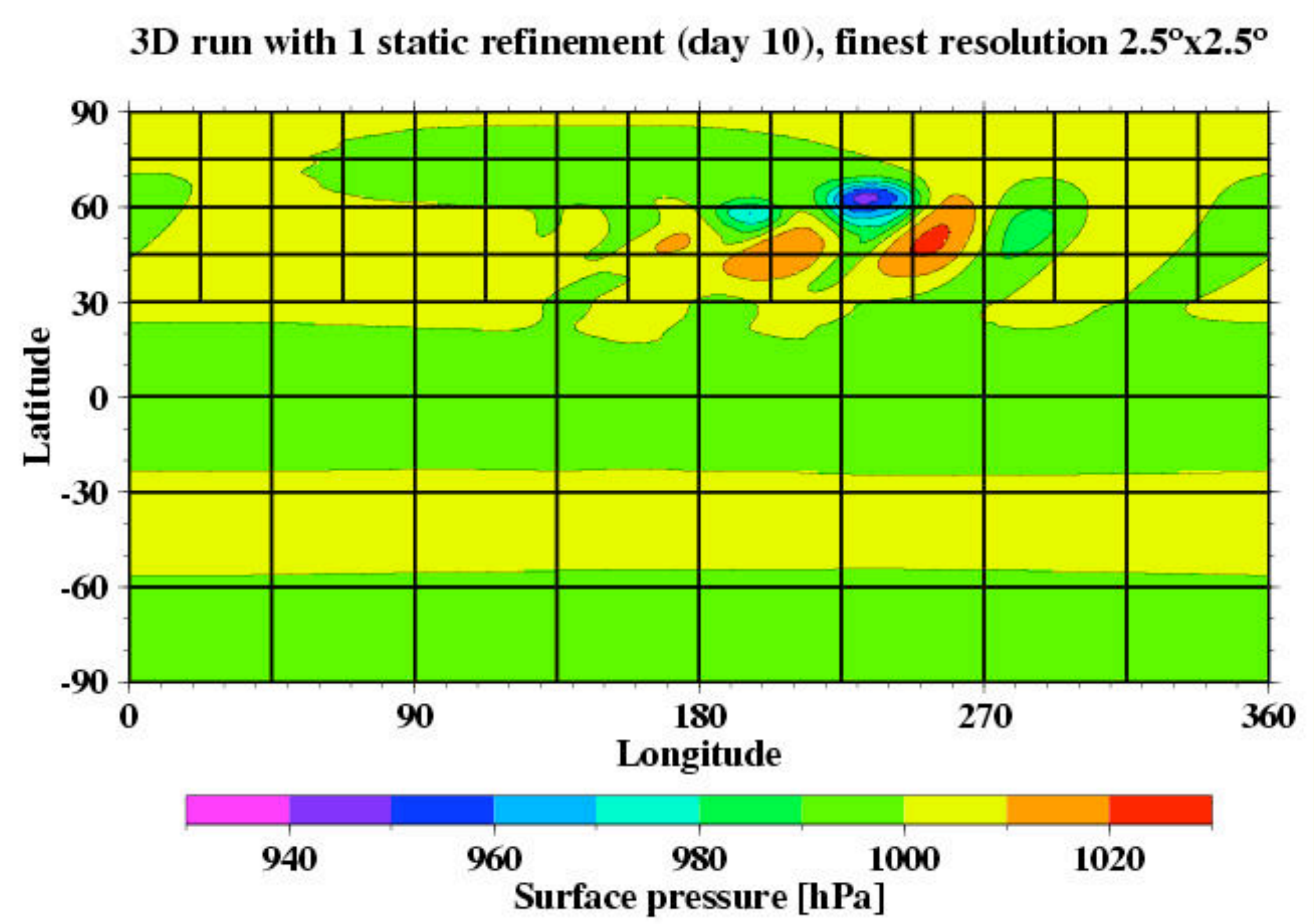
Baroclinic waves: 5° x 5° resolution

- JW baroclinic wave test case for dynamical cores (our test 2)
- Coarse resolution does not resolve the wave train



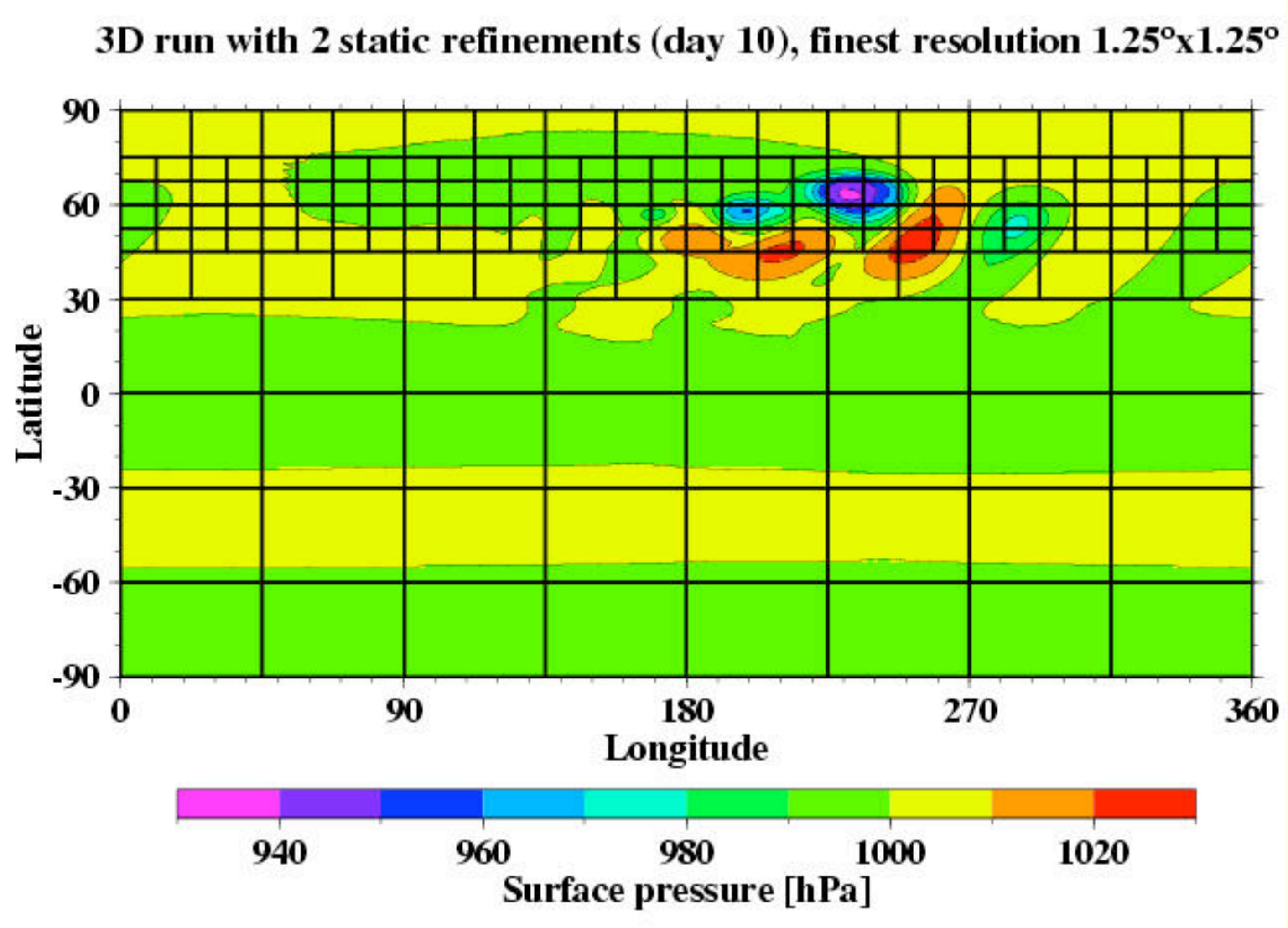
Static adaptations in 3D

- 1 Refinement along the storm track improves the simulation



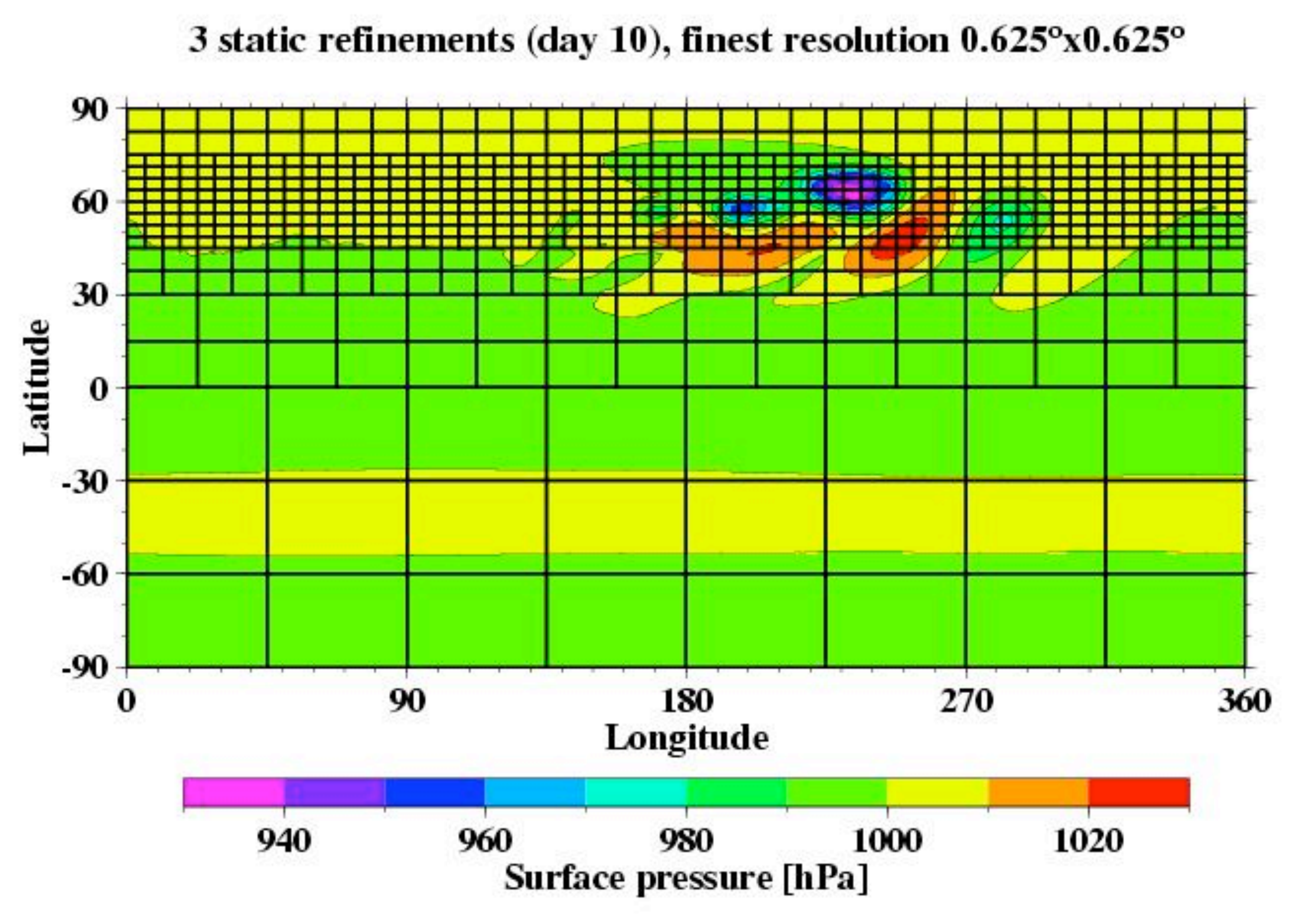
Static adaptations in 3D

- 2 Refinements along the storm track capture the wave accurately



Static adaptations in 3D

- 3 Refinements along the storm track: no further intensification



Conclusions

- Static and dynamic adaptive meshes are worth exploring for weather and climate applications
- Cubed-sphere or other non-traditional meshes together with AMR have clear advantages:
  - No convergence of any grid lines, no polar filters
  - Local grid adaptations are truly local
- Moving nested grids are already used for (regional) tropical cyclone simulations today (e.g. NCAR’s WRF model)
- Less clear whether dynamic adaptations can be successfully employed in climate models (remember teleconnection patterns), but static refinements are promising (e.g. near mountains, tropical channel)