Adaptive Grids for Weather and Climate Models

Christiane Jablonowski [1],

M. Herzog [2], **R. Oehmke** [2],

J. E. Penner [2], **Q. F. Stout** [2], **B. van Leer** [2]

[1] National Center for Atmospheric Research, Boulder, CO

[2] University of Michigan, Ann Arbor, MI

ECMWF Annual Seminar, September 2004

Overview of the talk

- Motivation: Atmospheric multi-scale regimes
- Overview of adaptive grid techniques
  - Static grid adaptations
  - Dynamic grid adaptations
- Introduction to the NASA/NCAR finite volume (FV) dynamical core
- Adaptive grid approach: Block-structured adaptive grids on the sphere
  - Adaptation strategy for static and dynamic adaptations
  - Adaptive spherical grid library for parallel processors
- Results: The statically and dynamically adaptive FV model
  - 2D shallow water experiments
  - 3D idealized dynamical core experiments
- Discussion: Adaptation criteria for real weather scenarios
- Conclusion and Outlook

Features of Interest in a Multi-Scale Regime

Hurricane Frances

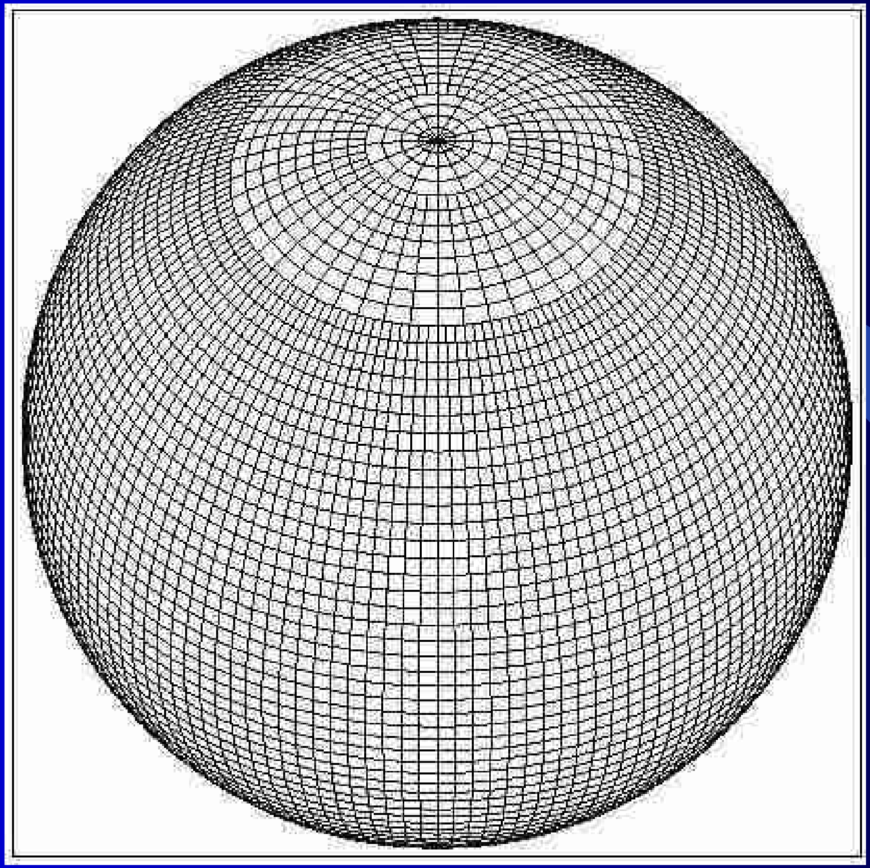
Hurricane Ivan

September/5/2004

Adaptive Grids for 3D Atmospheric Models

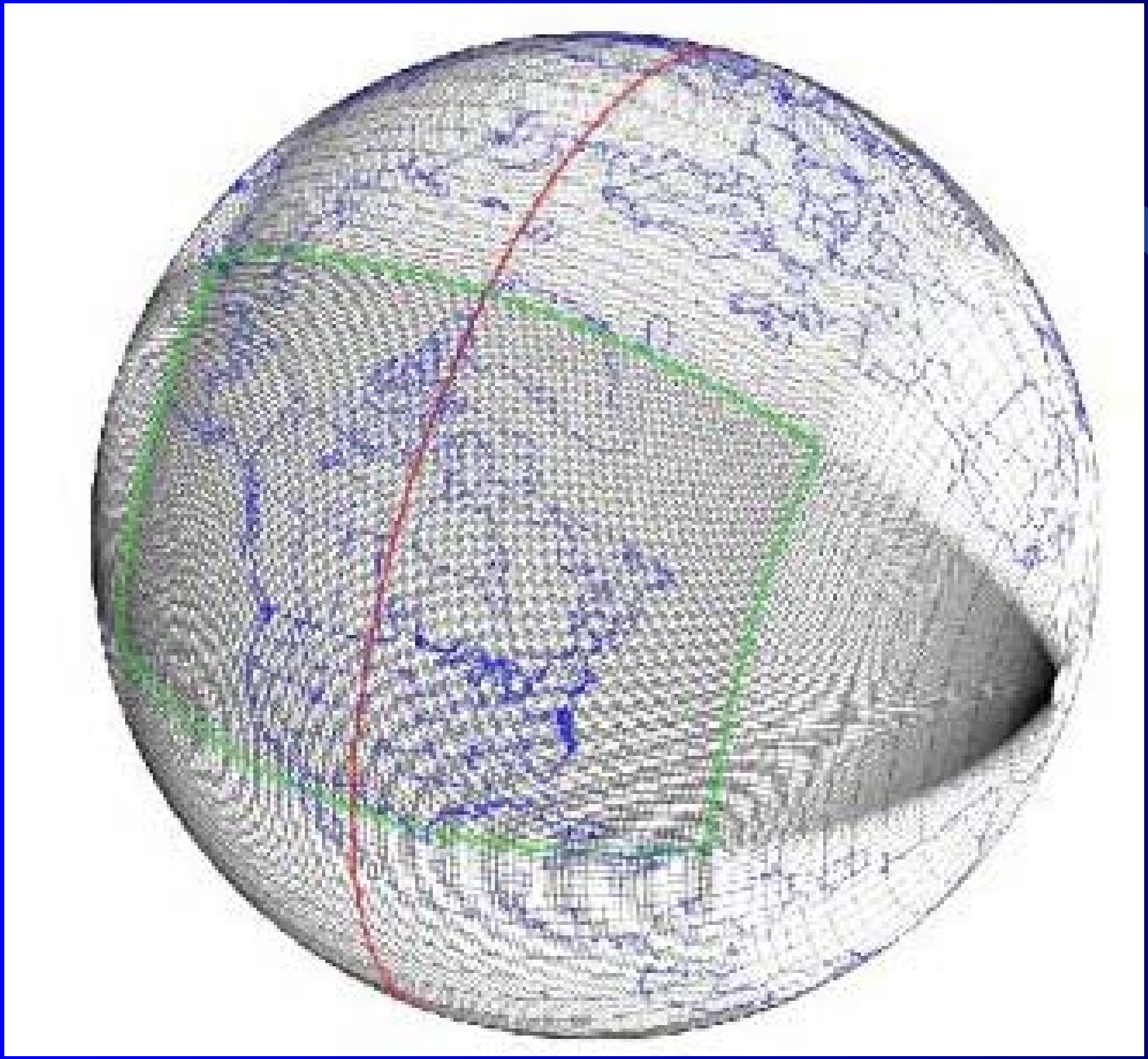
- Statically adaptive grids
  - Reduced grid
  - Stretched grids
  - Transformed grids (e.g. Schmidt coordinate transformation)
  - Unstructured grids
  - Nested grids
- Dynamically adaptive grids
  - Irregular data structures: triangulated grids
    (Bacon et al., MWR 1998, Gopalakrishnan et al., MWR 2002)
  - Regular data structures: block-structured lat-lon grid
    (Skamarock et al., JCP 1989, Hubbard and Nikiforadis, MWR 2003, Jablonowski et al. 2004)
  - Cubed sphere with spectral element formulation:
    active research by A. St-Cyr, S. Thomas and J. Dennis (NCAR)

Static Adaptations: Reduced Grids



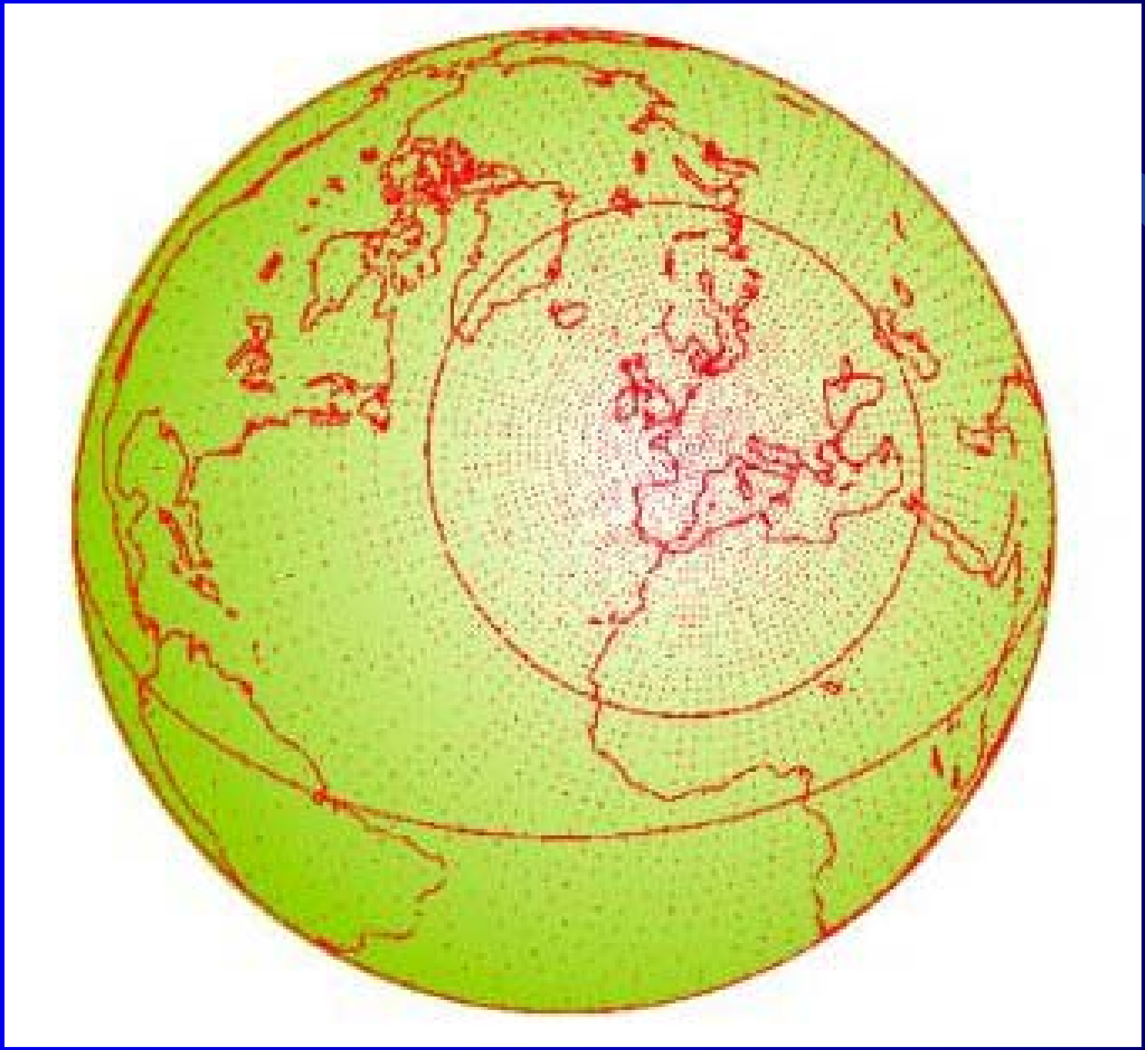
- Number of grid cells in longitudinal direction is reduced towards high latitudes
- Keeps the resolution more uniform, allows longer time steps

Static Adaptations: Stretched Grids



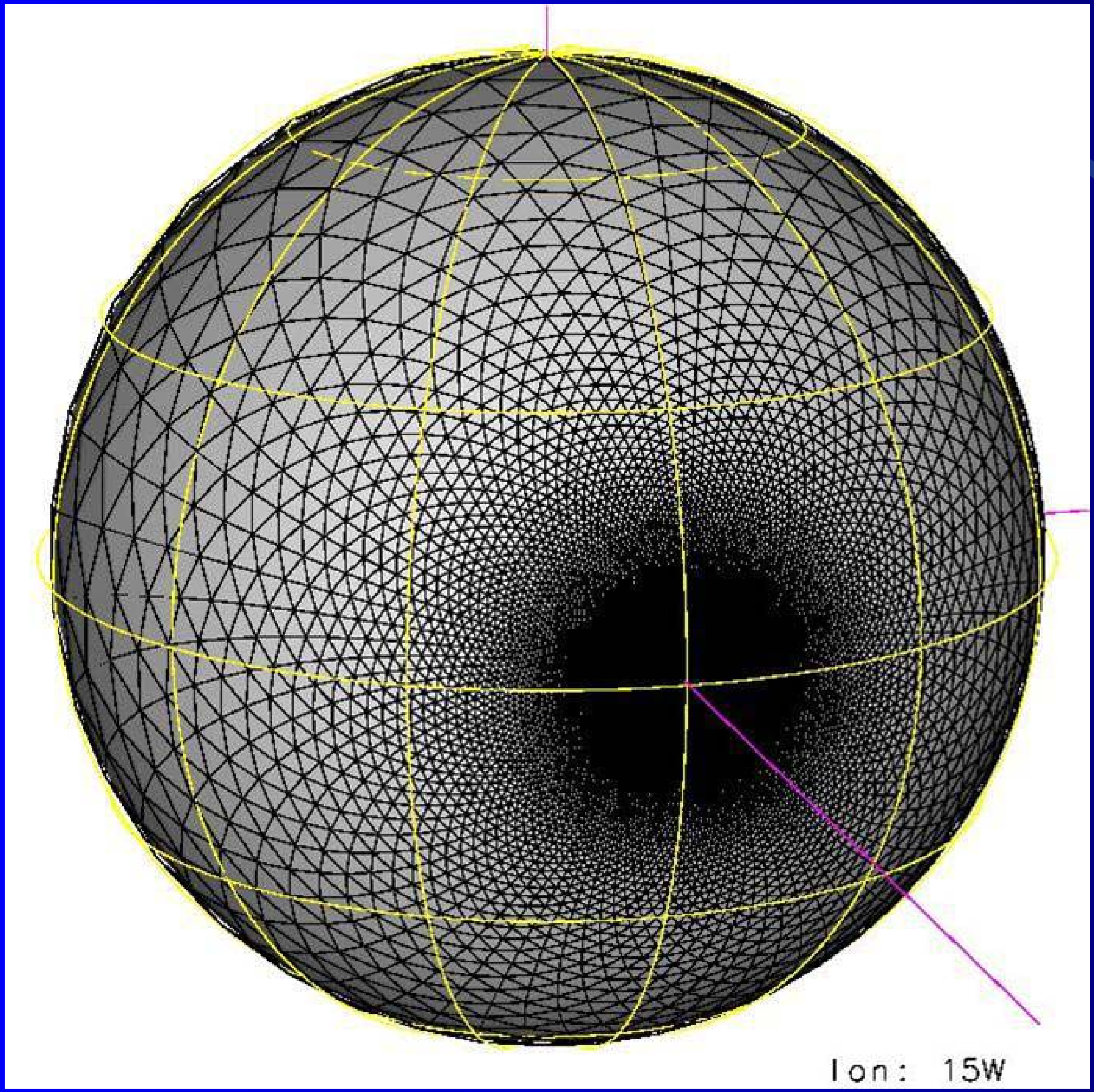
GEM
Canadian Model

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



Model Arpege
Meteo France

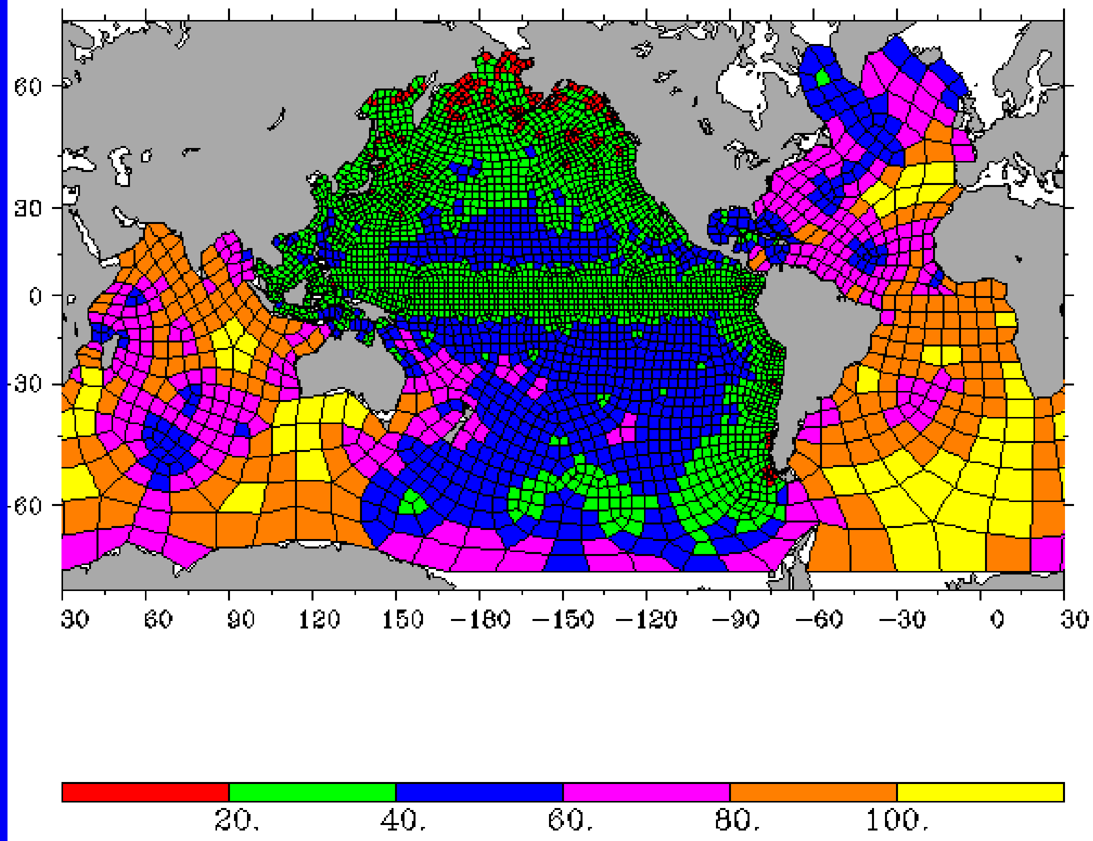
Static Adaptations: Stretched Icosahedral Grid (Schmidt transformation)



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



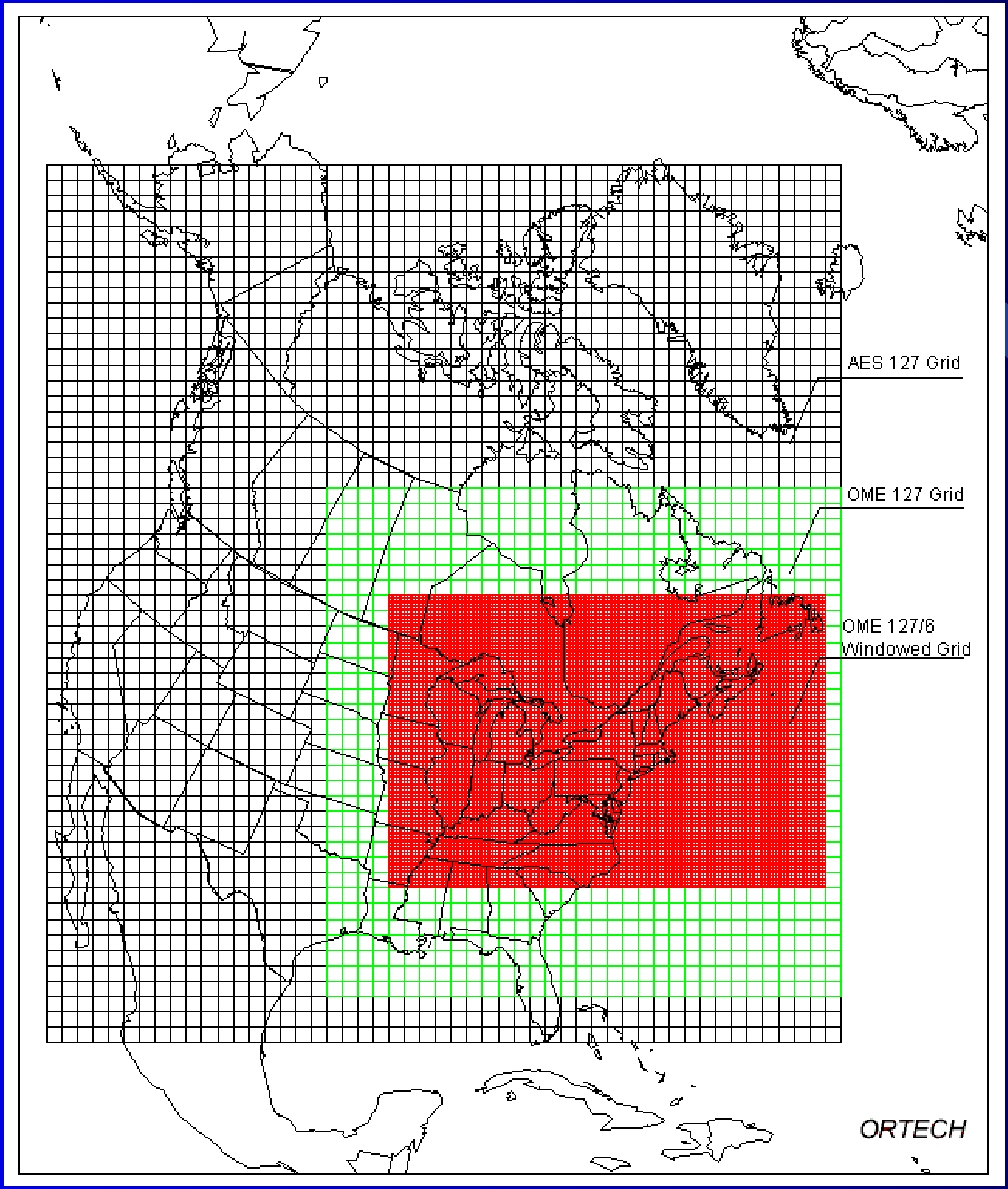
Average grid spacing (km) within each element

Spectral elements allow flexible configurations:

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

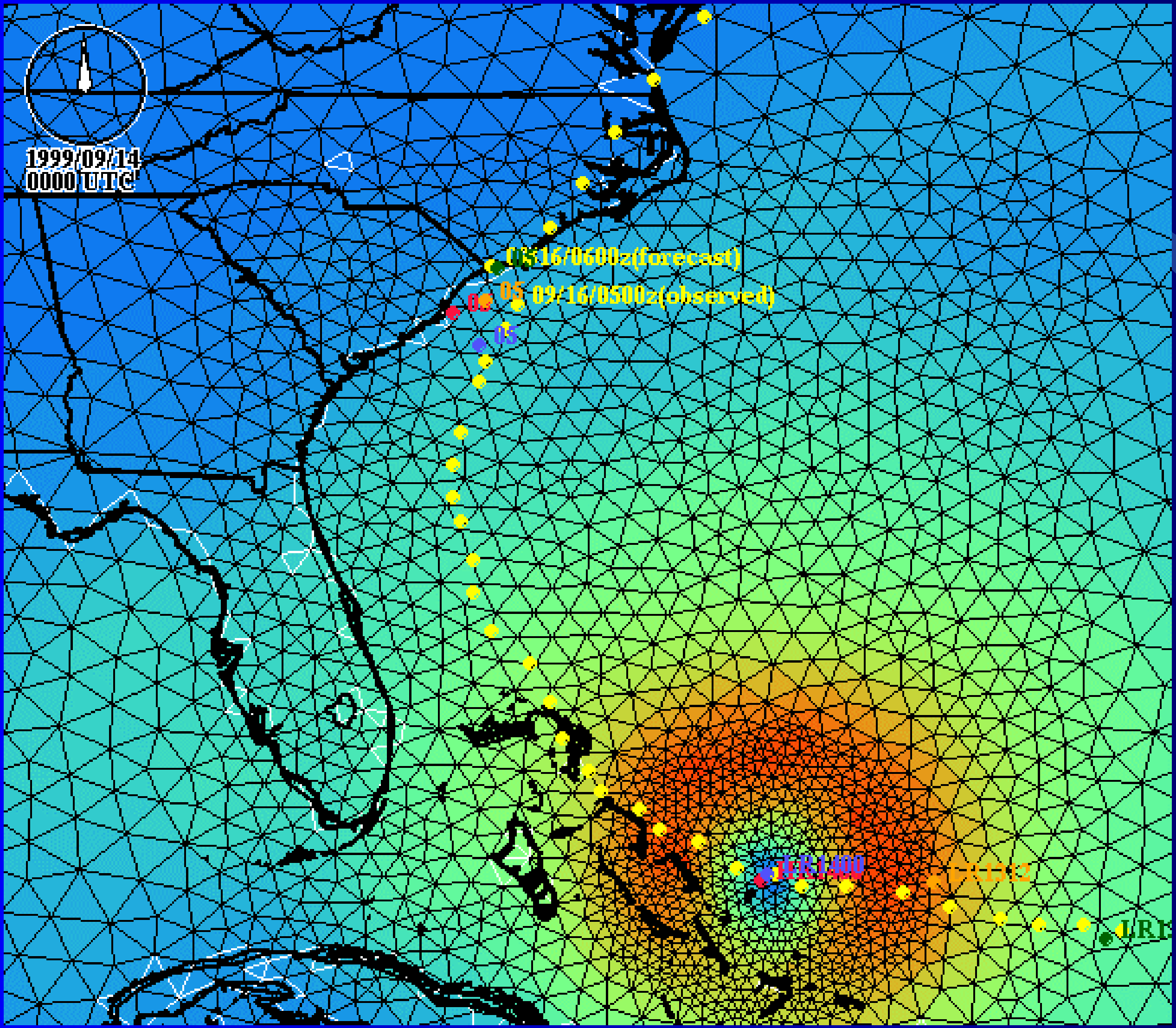
Source:
Rutgers University

Static adaptations: (Multiple) Nested Grids



Canadian Model

Dynamic Adaptations: Irregular Triangular Grid



Hurricane Floyd (1999)

OMEGA model

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

Colors indicate the wind speed

Adaptive Grids for Weather and Climate Models

- **Research goal:** Build a hydrostatic (and later a non-hydrostatic) dynamical core for a future General Circulation Model (GCM) that can statically and dynamically adapt its horizontal resolution with respect to
  - regions of interest (e.g. mountain regions)
  - features of interest (e.g. low pressure systems, convection?, fronts?)

- Scientific computing challenge: Interdisciplinary team effort with the University of Michigan
  - Atmospheric science (Joyce Penner, Michael Herzog)
  - Numerics (Bram van Leer, Ken Powell)
  - Computer Science (Robert Oehmke, Quentin Stout)

- Collaboration with NASA / GSFC: S.-J. Lin and Kevin Yeh

The NASA/NCAR finite volume dynamical core

- 3D hydrostatic dynamical core for climate and weather prediction (also called Lin-Rood dynamical core):
  - 2D horizontal equations are the shallow water equations
  - 3^{rd} dimension in the vertical direction is a floating Lagrangian coordinate

➡ 2D model is 1-level version of the dynamical core: Idealized test bed

- **Numerics:** Finite volume approach
  - conservative and monotonic transport scheme
  - upwind biased 1D fluxes, operator splitting
  - 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)

The 3D Lin-Rood Finite-Volume Dynamical Core

Momentum equation in vector-invariant form

$$\frac{\partial \vec{v}_h}{\partial t} + (\zeta + f)\vec{k} \times \vec{v}_h + \vec{\nabla} K + \vec{\nabla}_p \Phi = 0$$

$$\vec{\nabla}\Phi + \frac{1}{\rho}\vec{\nabla} p$$

Pressure gradient term in finite volume form

Continuity equation

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

Thermodynamic equation

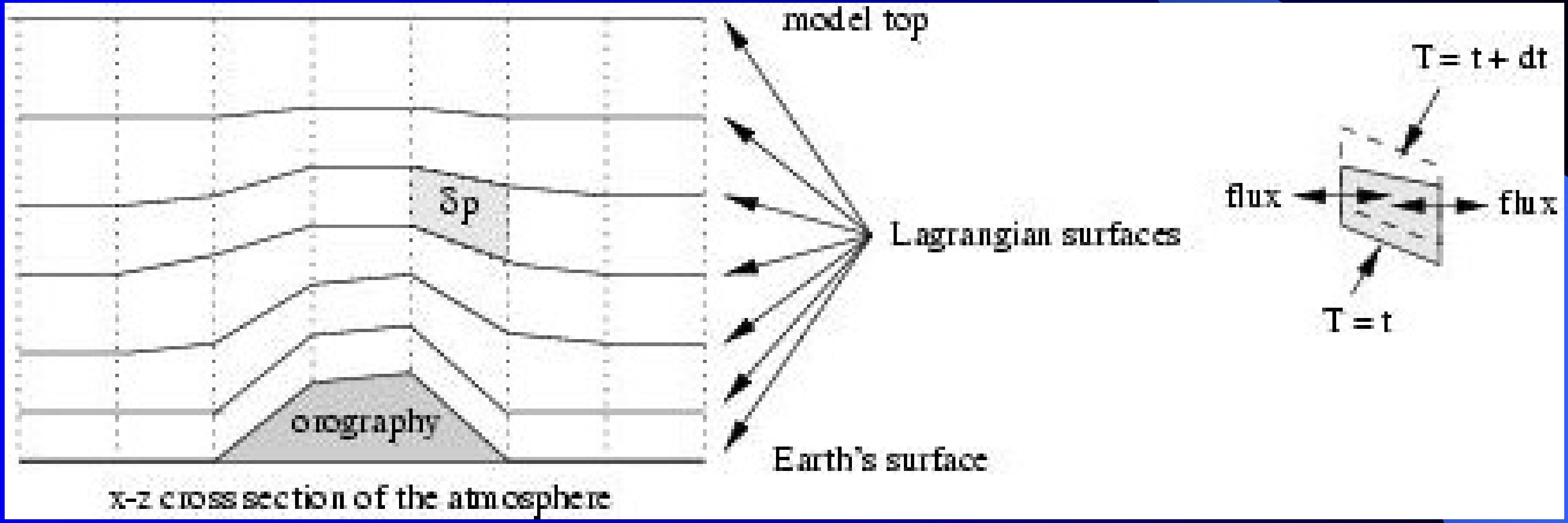
$$\frac{\partial (\delta p \Theta)}{\partial t} + \vec{\nabla} \bullet (\delta p \Theta \vec{v}) = 0$$

The prognostics variables are: $u, v, \Theta, \delta p = -\rho g \delta z$

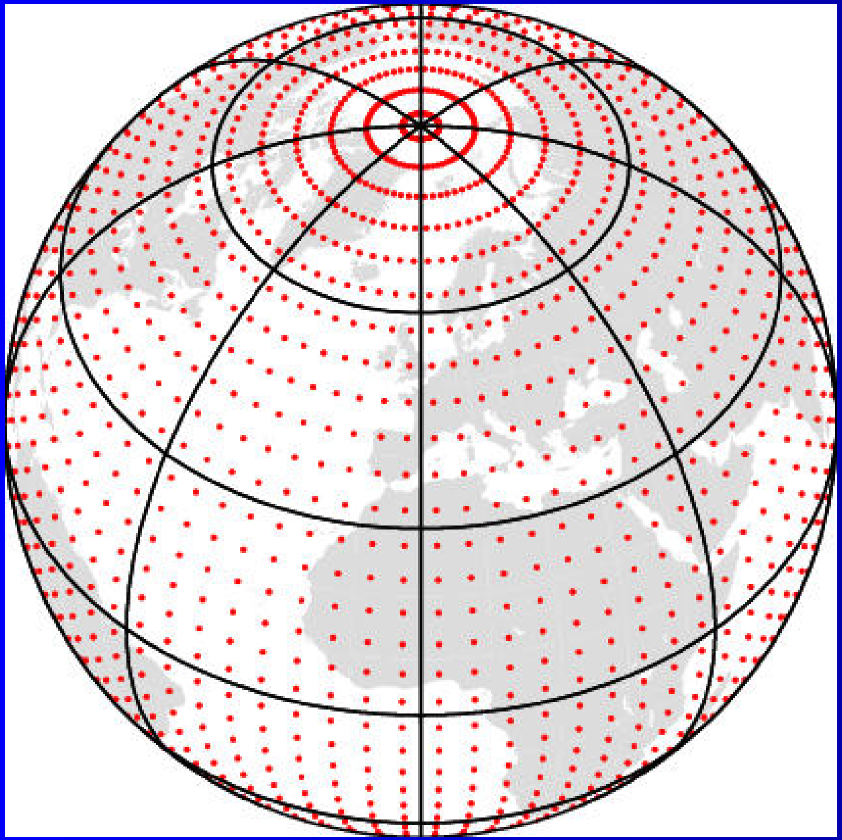
δp: pressure thickness

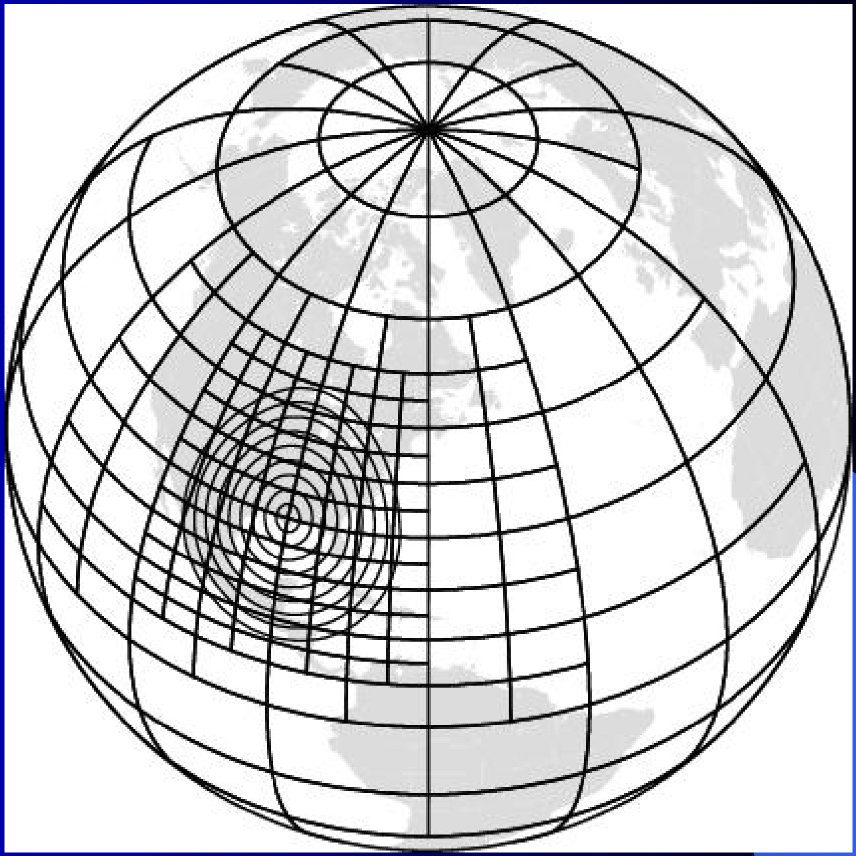
Floating Lagrangian Vertical Coordinate

- 2D transport calculations within floating Lagrangian layers
- Layers are material surfaces, no vertical advection
- Periodic re-mapping of the Lagrangian layers onto reference grid



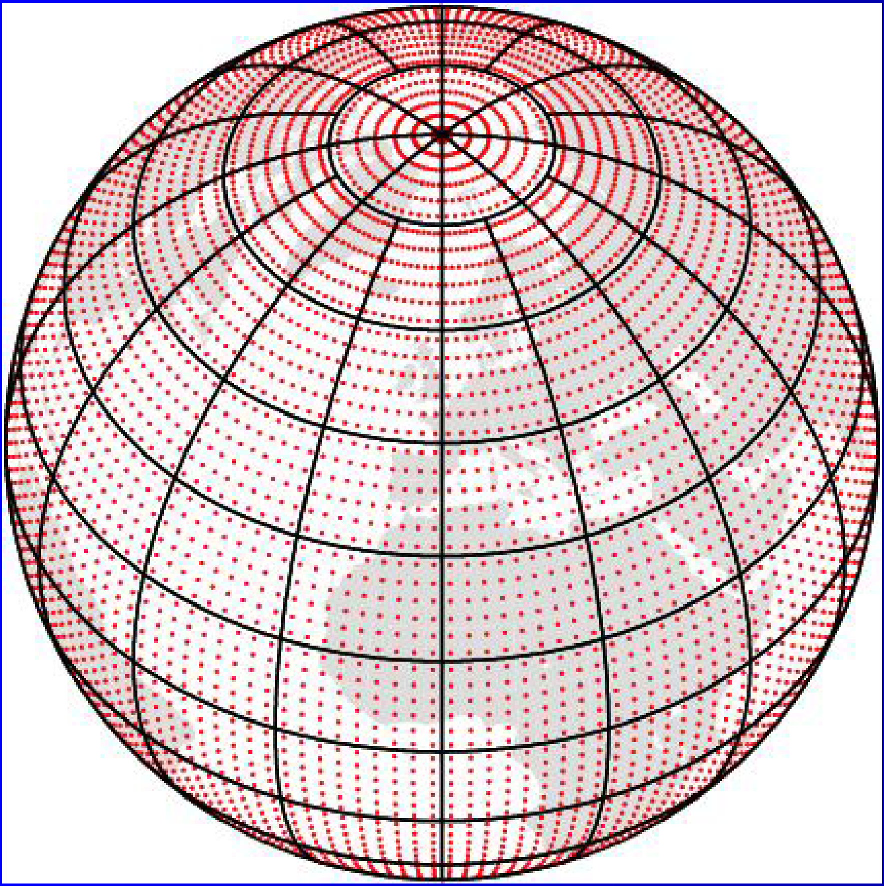
Adaptive Mesh Refinement Strategy in Spherical Geometry



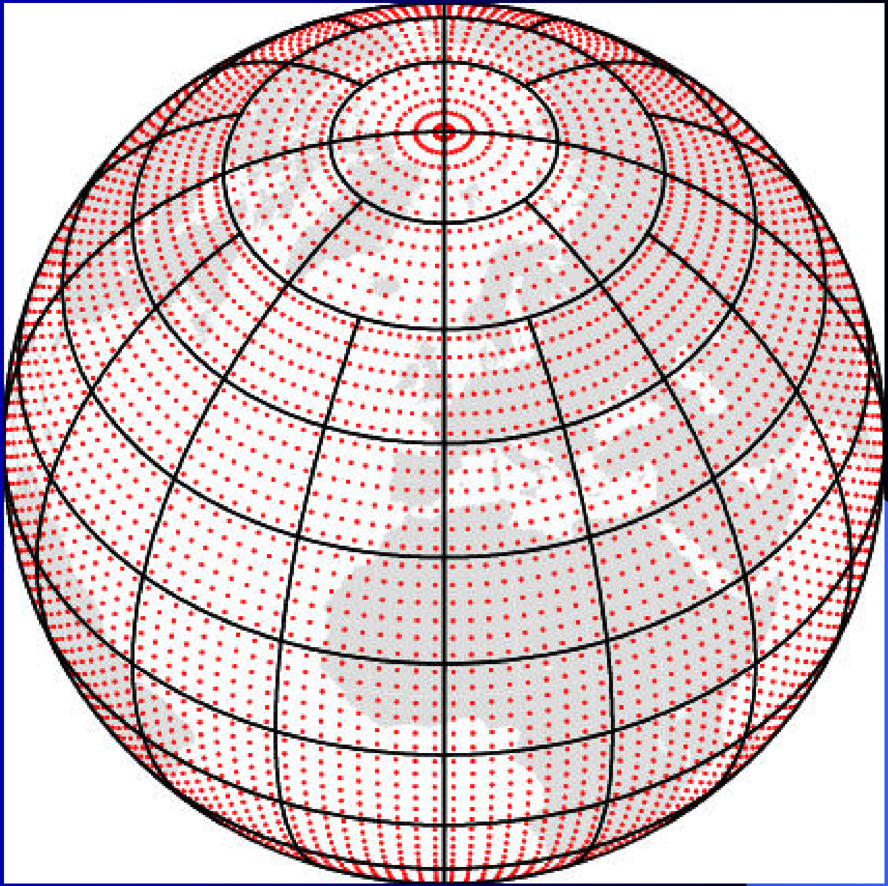


Self-similar blocks with 3 ghost cells in x & y direction

Block-data structure and Reduced Grids

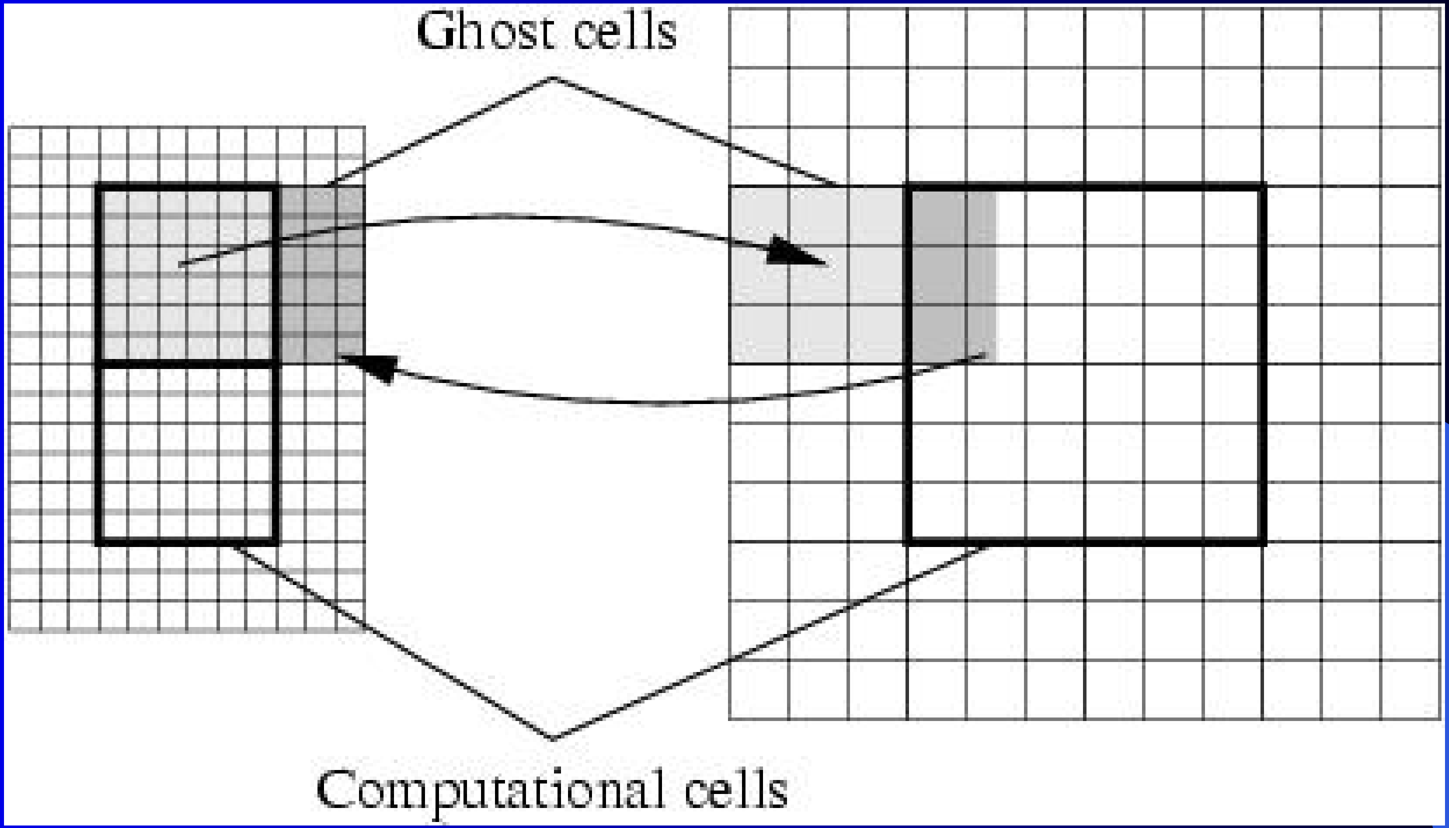


1 reduction level

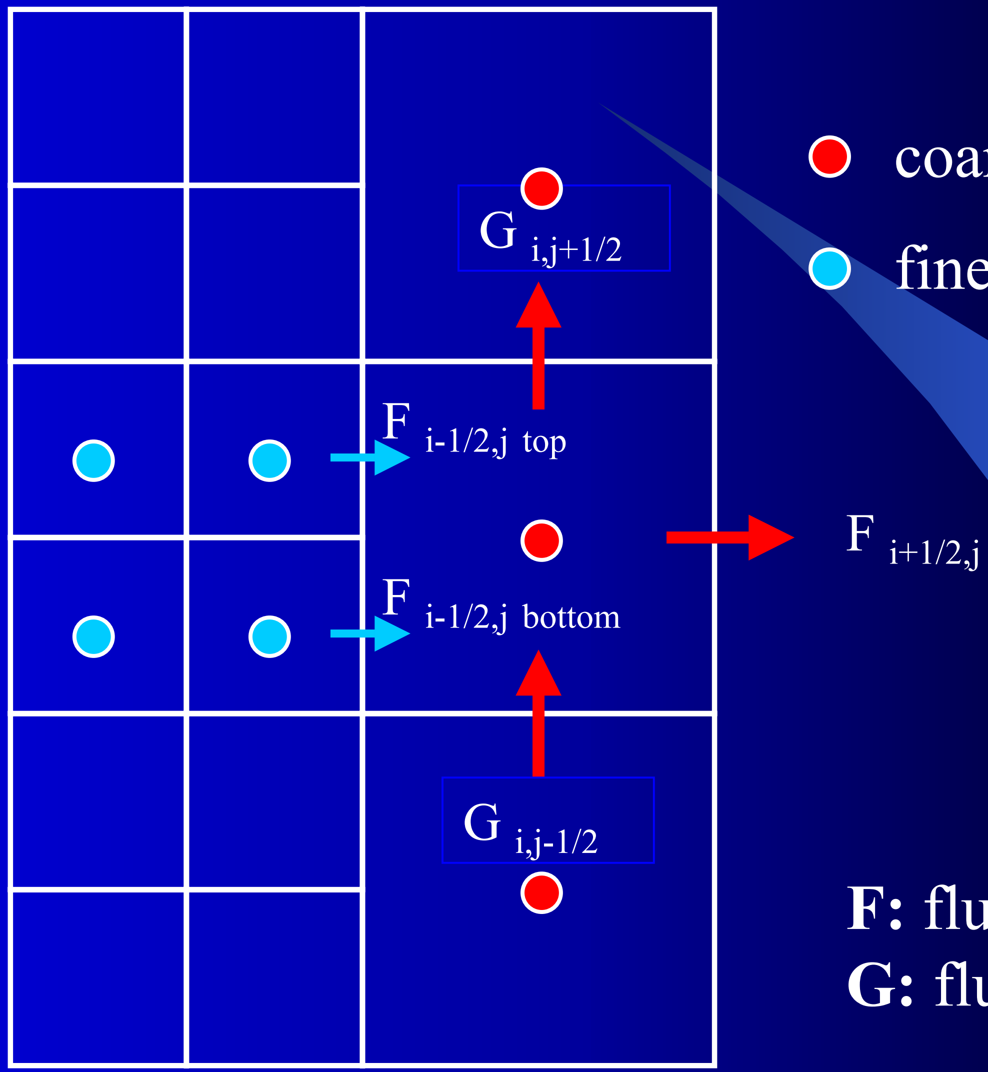


2 reduction levels

Ghost cell exchange at fine-coarse interfaces



Fine – coarse grid interface: Fluxes across boundaries



Ensure mass conservation: flux averaging with surface area weights

F: fluxes in x dir.
G: fluxes in y dir.

Spherical Adaptive Grid Library

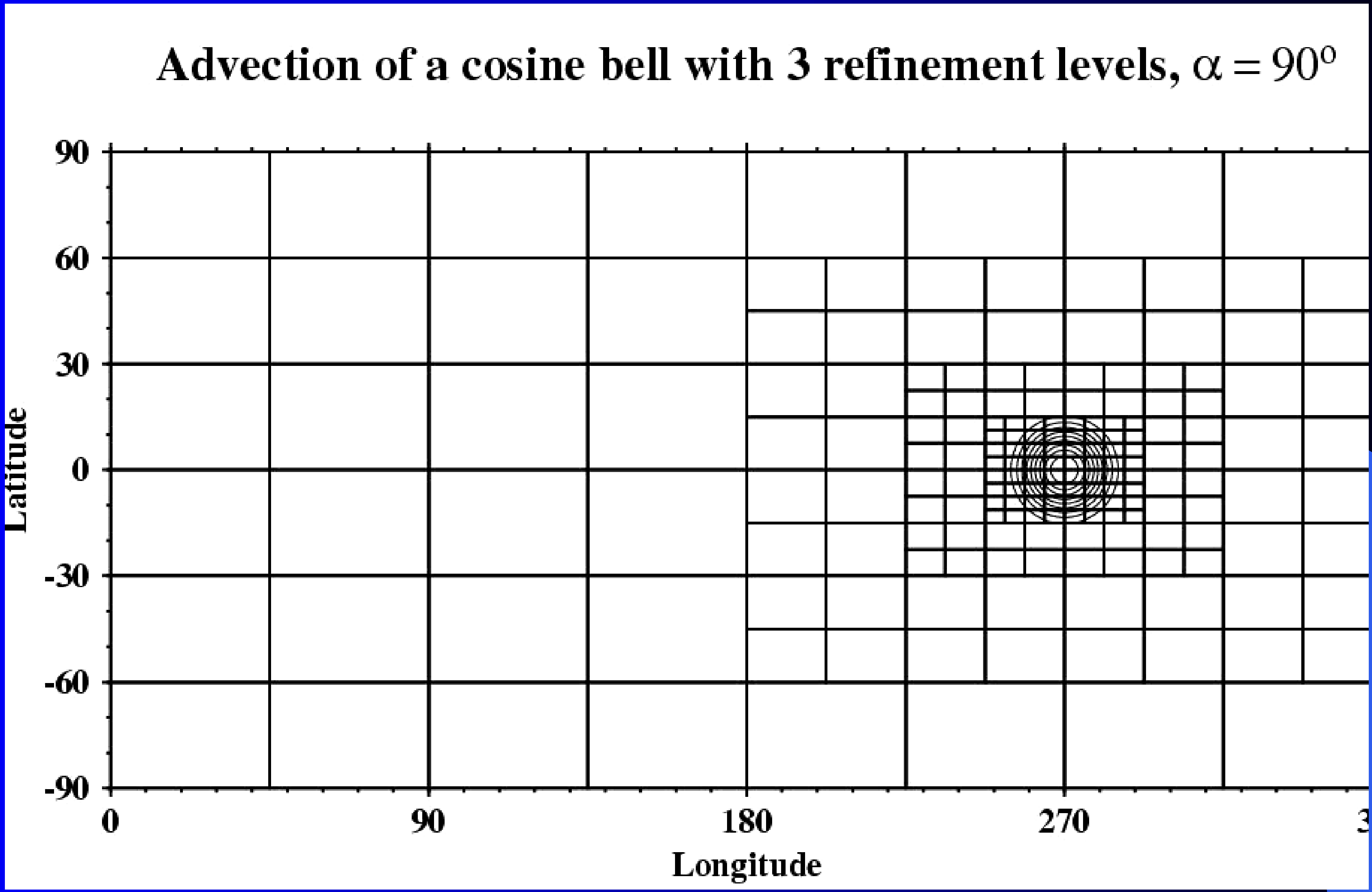
- Block management is done by a Spherical Adaptive Grid Library: developed by Robert Oehmke & Quentin Stout (U of Michigan)
- Designed for distributed memory parallel computers

- **Library manages:**
  - Definition and distribution of the sphere: Initial grid setup
  - MPI communication among neighboring blocks
  - Load balancing: e.g. equal number of blocks on each processor
  - Adaptive grids: generation/destruction of blocks, keeps track of neighbors
  - Iterations through the blocks
- **User supplied routines:**
  - Pack/unpack routines for boundary exchanges
  - Split / Join operations for boundary exchange if neighboring blocks are at different resolutions
  - Interpolation routines for data in newly refined/coarsened blocks

Overview of results: Highlights

- 2D shallow water tests:
  (Williamson et al., JCP 1992 test suite)
  - First glimpse: Track the features of interest
    - Advection experiments (test case 1)
    - Advection with a reduced grid
  - Static refinements in regions of interest (test case 2)
  - Dynamic refinements and refinement criteria:
    Flow over a mountain (test case 5)
- 3D dynamical core tests:
  - Static refinements along the storm track
  - Dynamic refinements with vorticity criterion

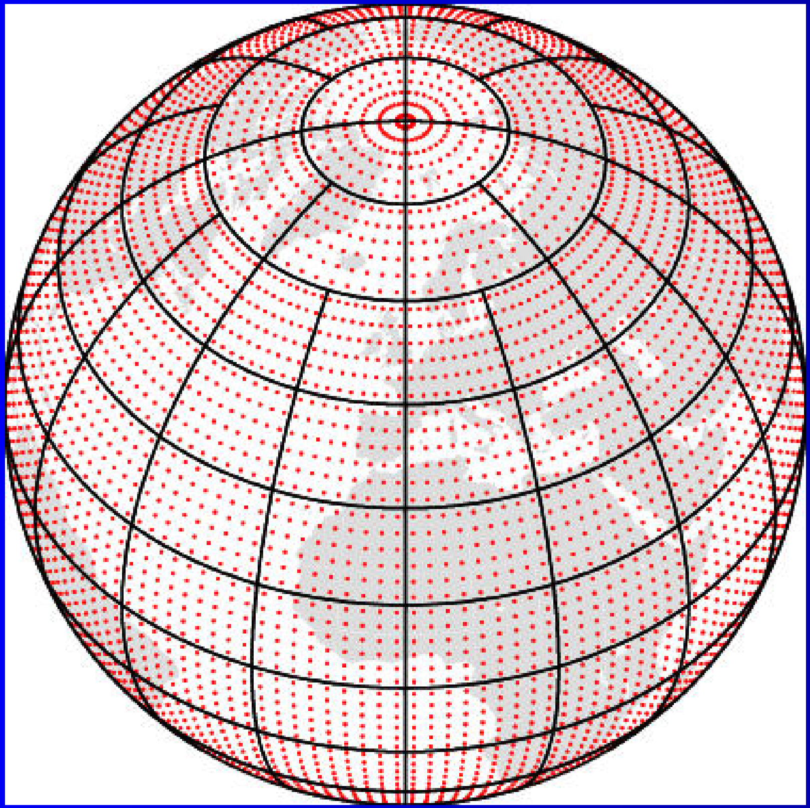
First glimpse: Adaptations at work

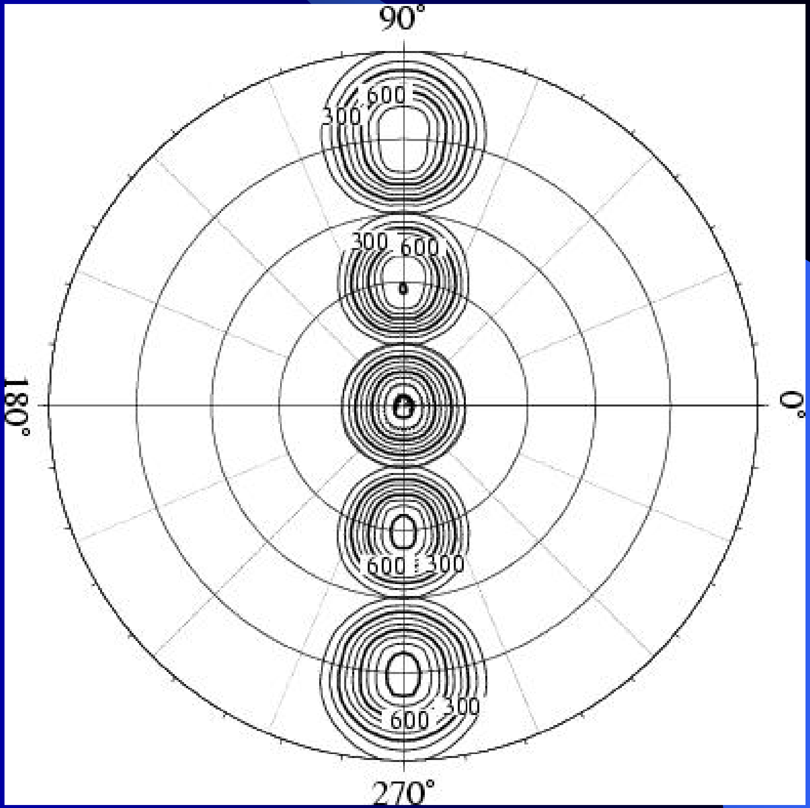


Dynamic adaptations and the reduced grid

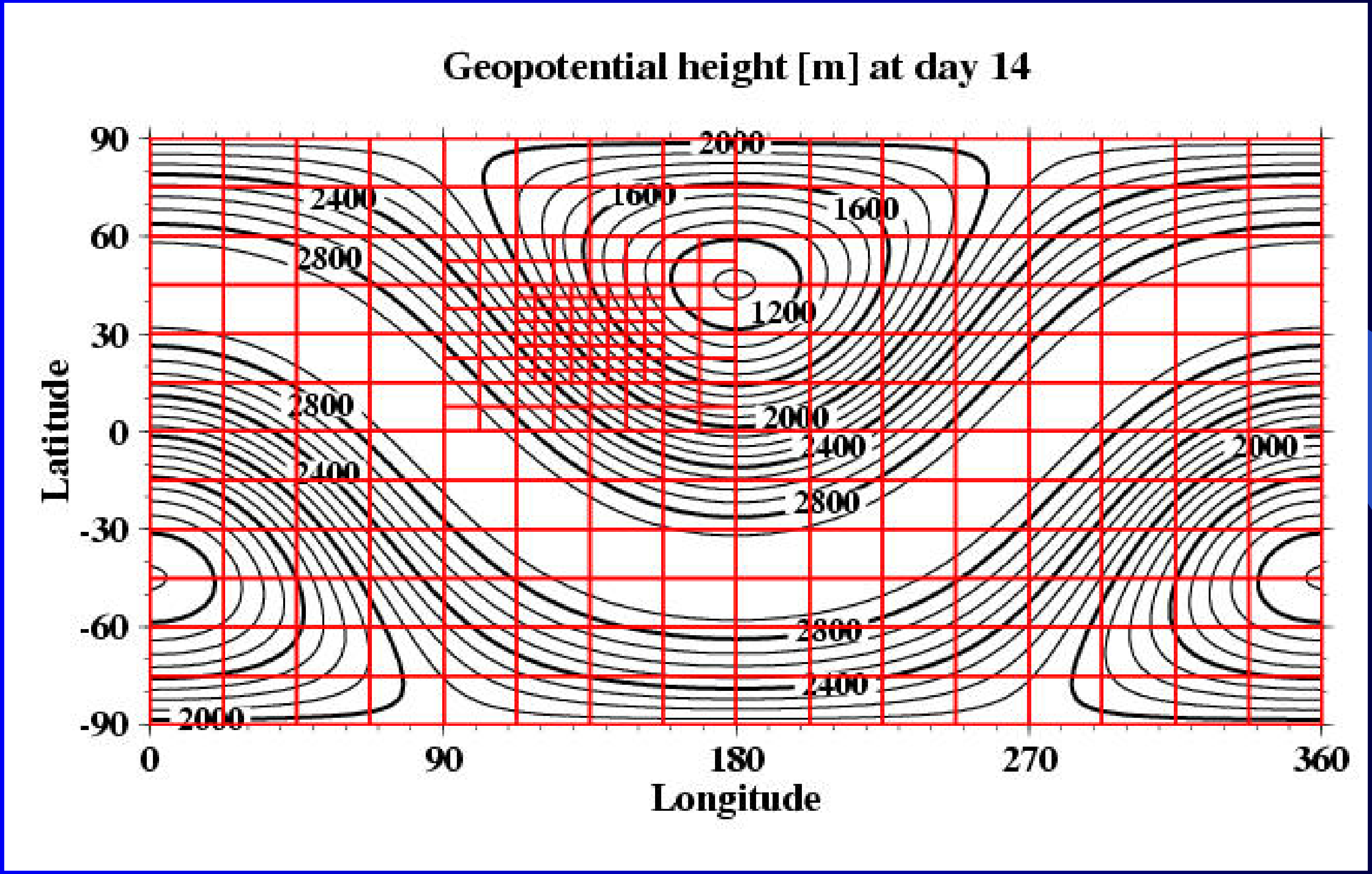
2 reductions

- No noise or distortions
- accurate transport





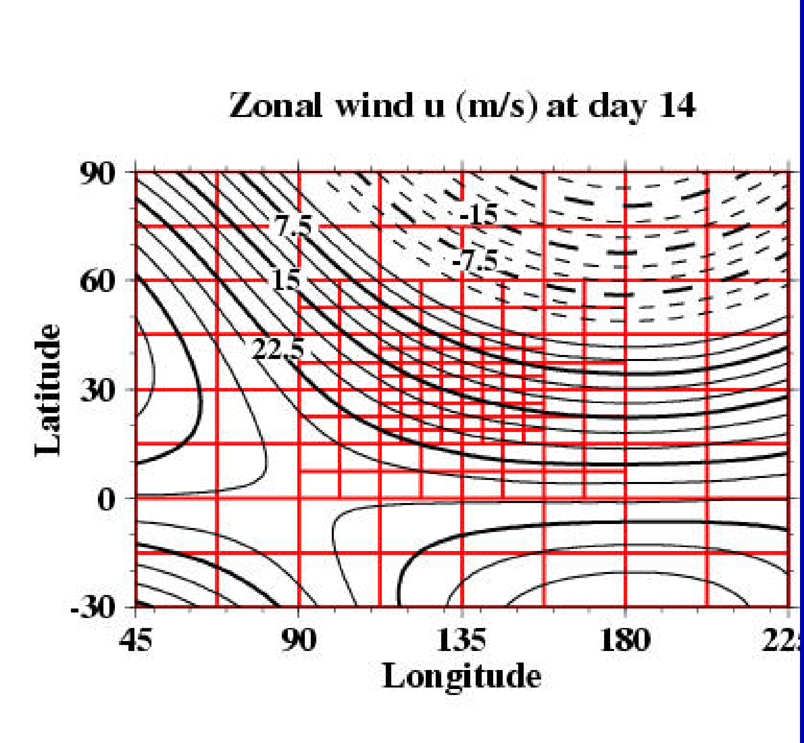
2D Static adaptations: Region of interest

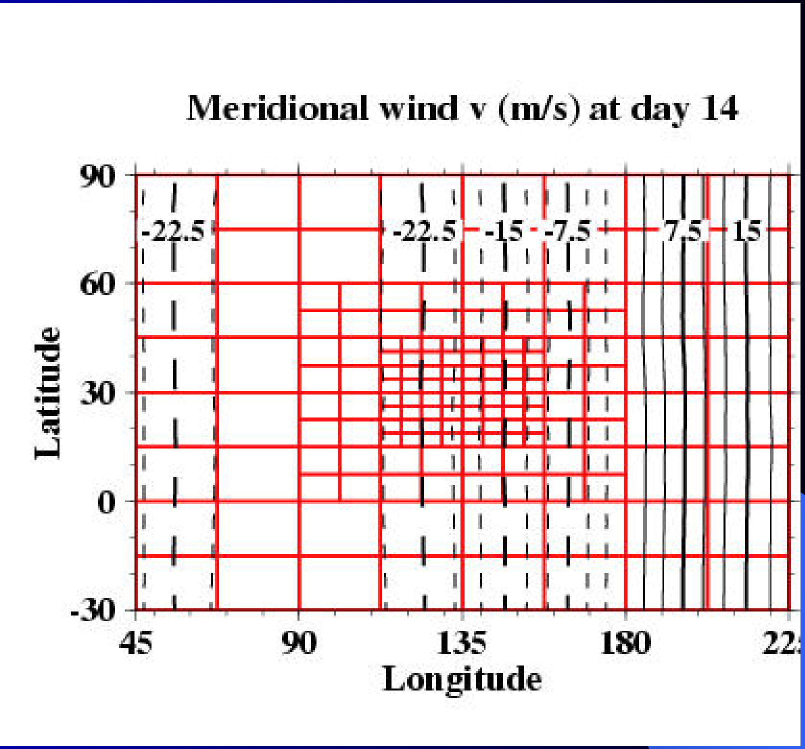


Test case 2, $\alpha = 45$

- Smooth flow in regimes with strong gradients

2D Static adaptations: Closer look



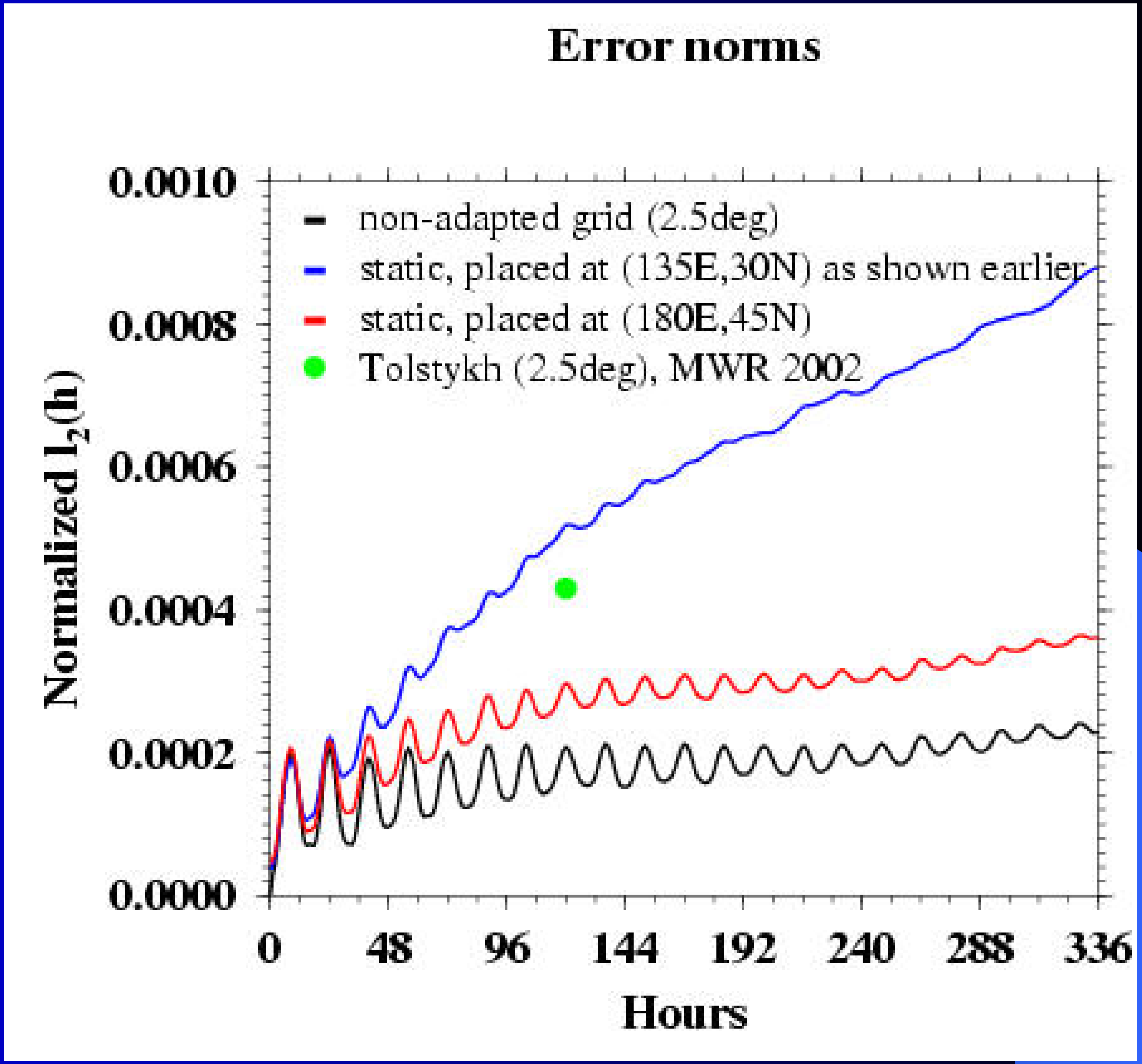


- Smooth wind field
- No severe noise or distortions at the fine-coarse grid interface

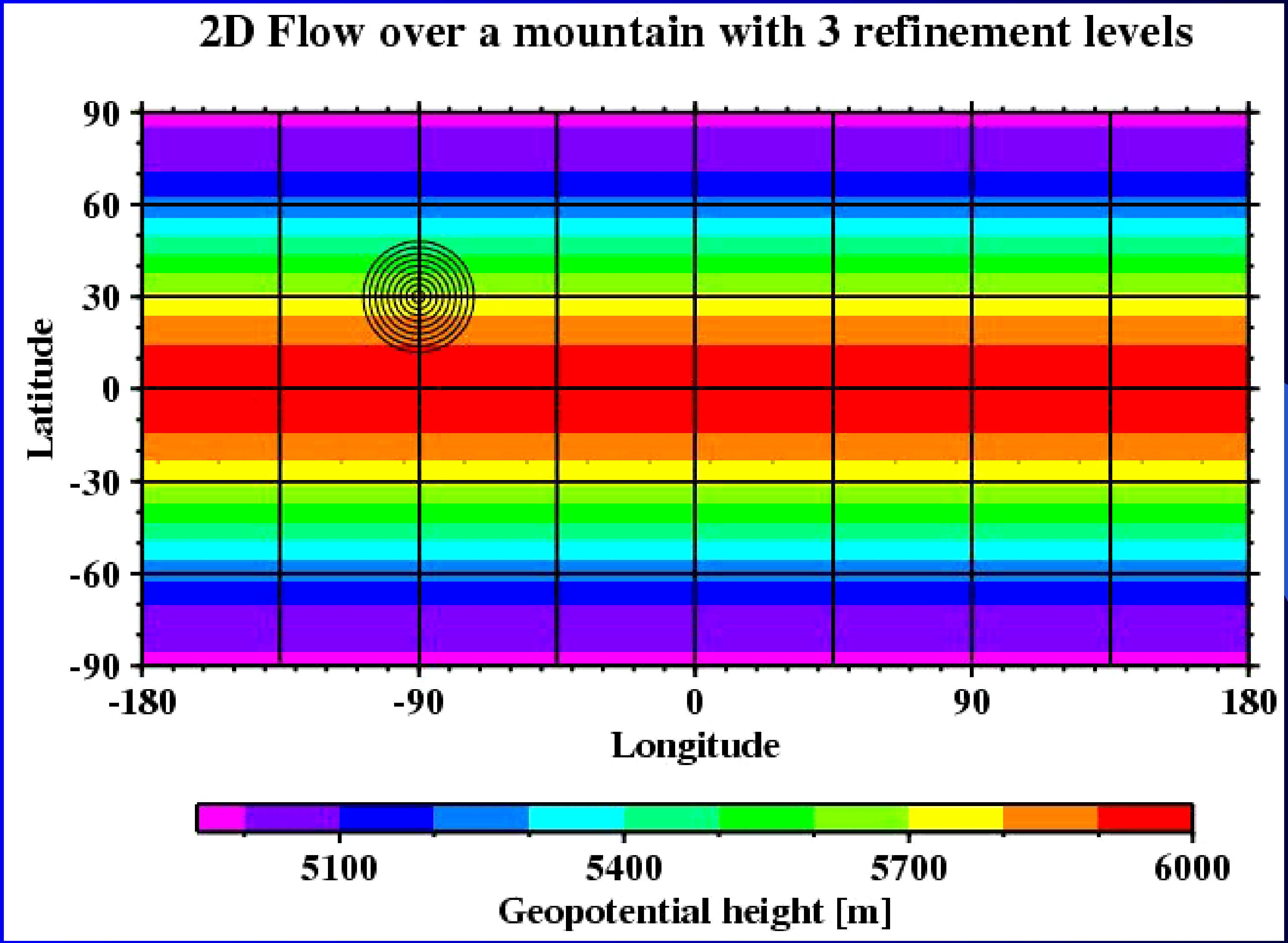
2D Static adaptations: Error norms

Test case 2, $\alpha = 45$:

- Errors at grid interfaces are moderate
- Errors increase in regions with strong gradients



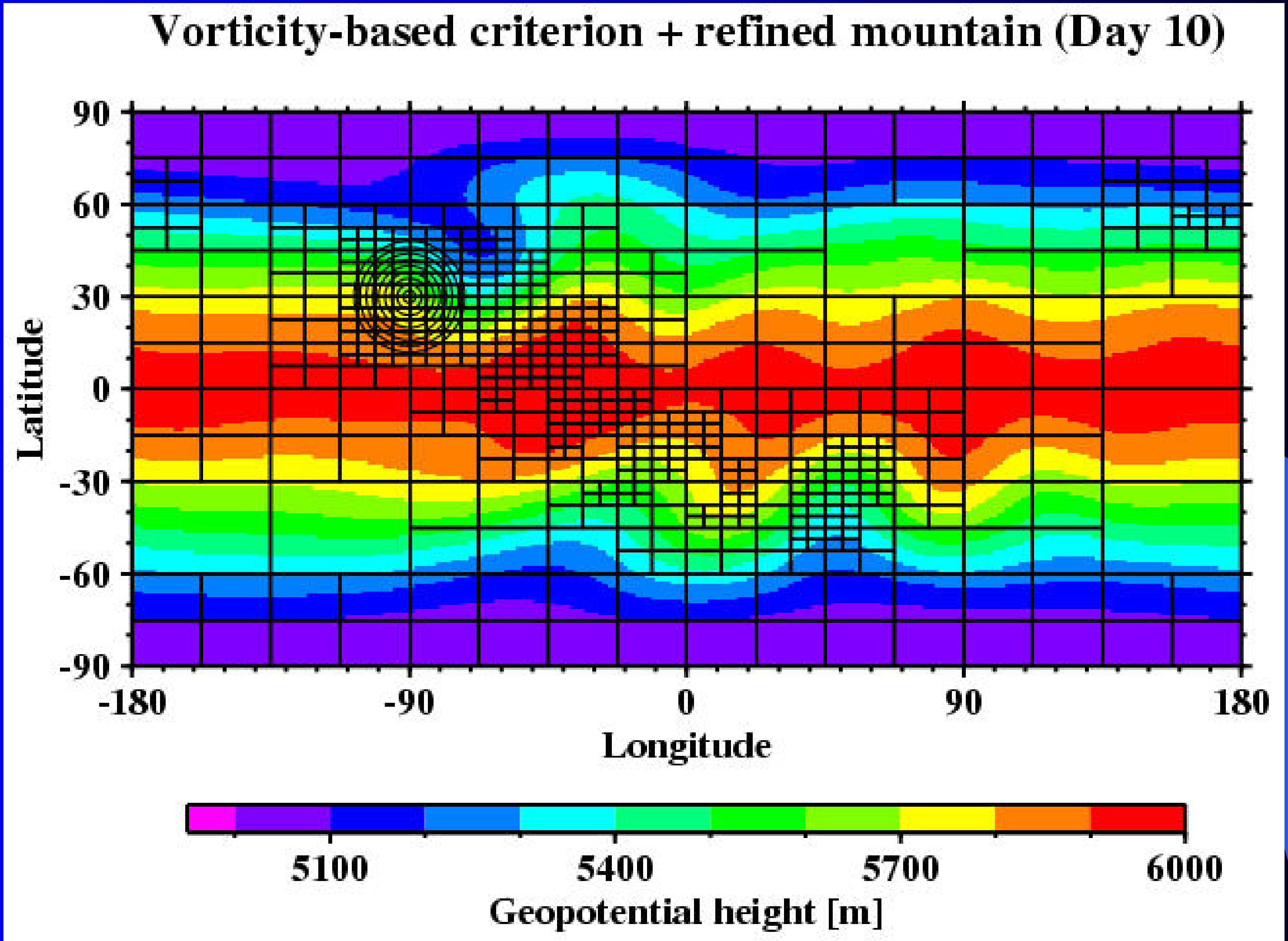
2D Dynamic adaptations



Test case 5

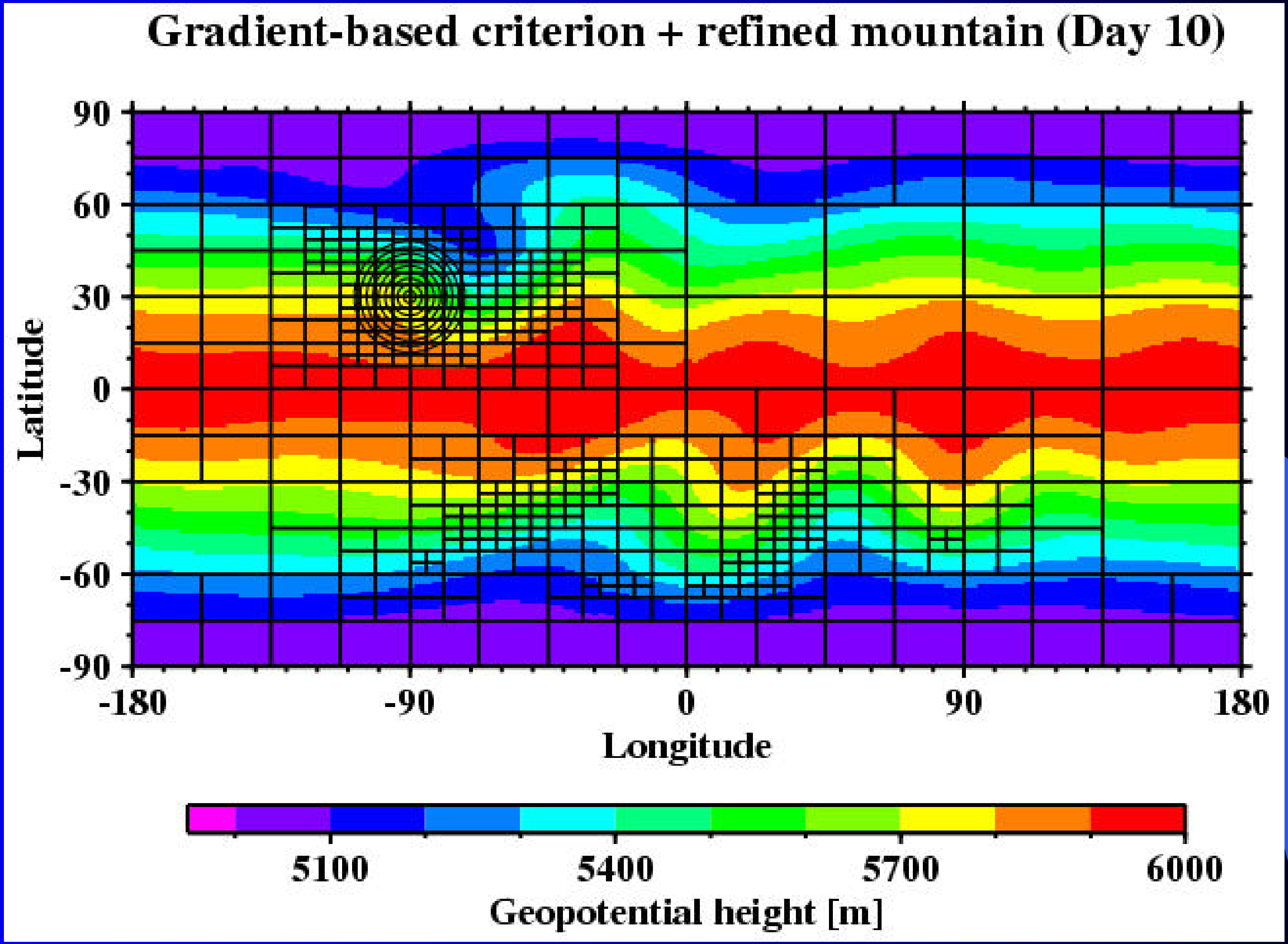
Adaptation criterion: based on the gradient of the geopotential height field

Adaptation criterion: Vorticity



Vorticity criterion detects regions with strong curvature

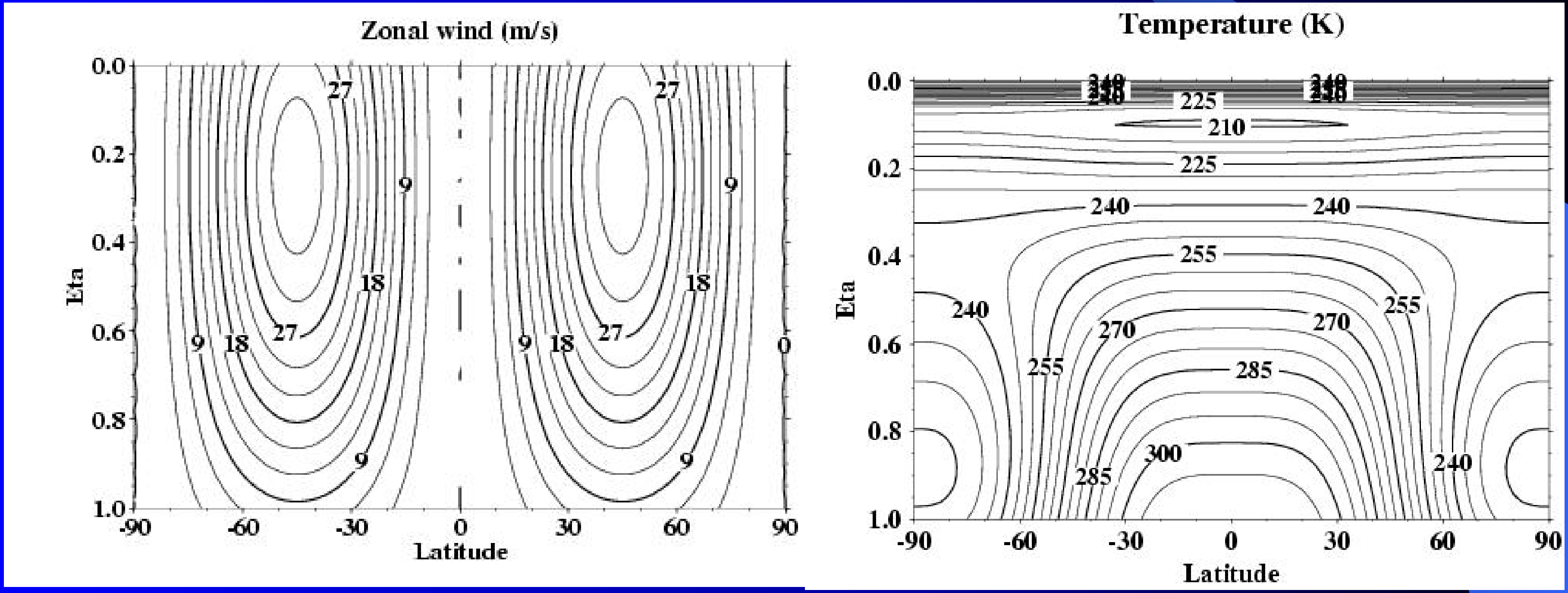
Adaptation criterion: Geopotential gradient



Gradient criterion detects disconnected regions of the wave train

Baroclinic wave test case

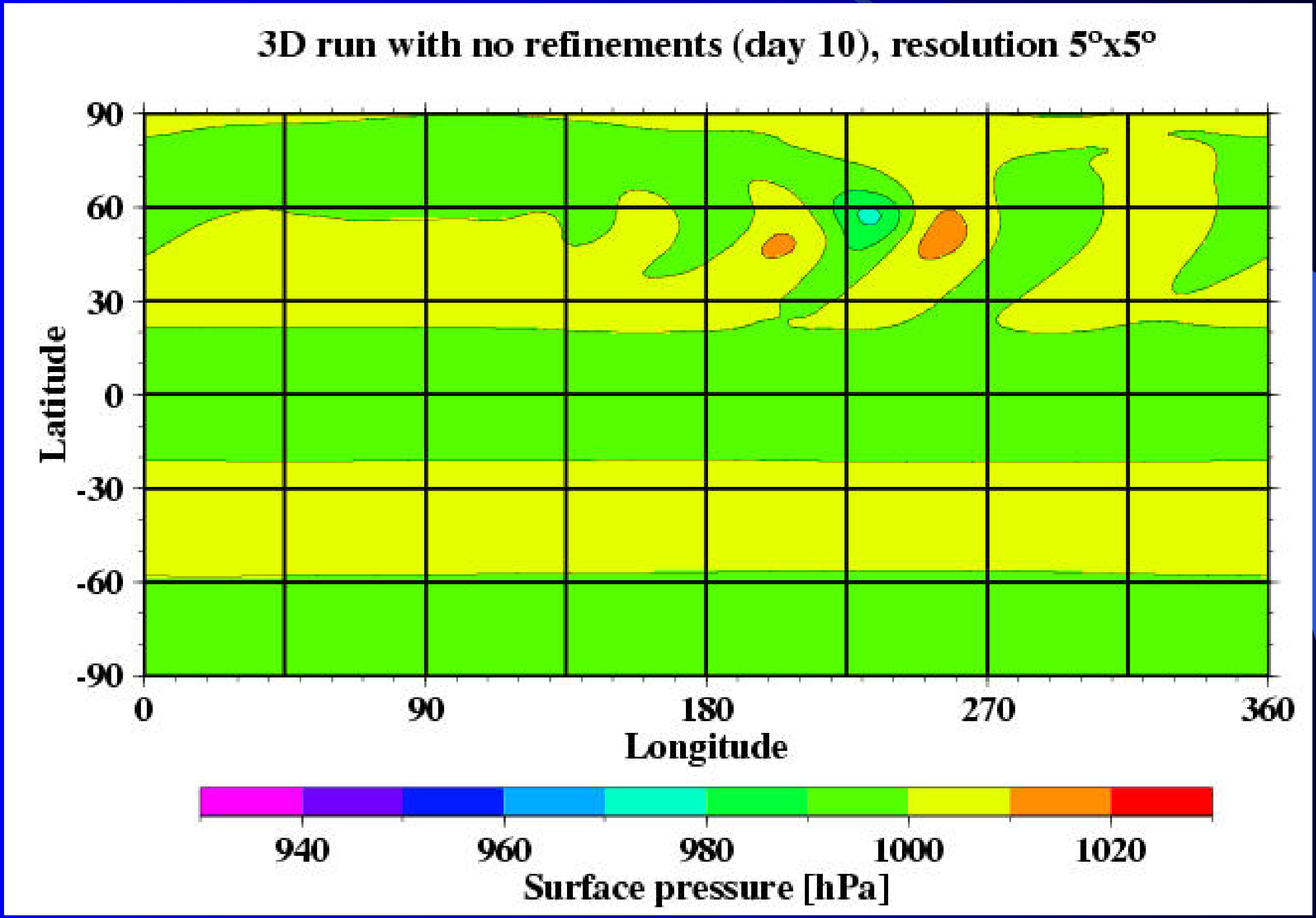
- analytically specified balanced initial field with overlaid perturbation
- baroclinic wave develops after 5-10 days
- deterministic test that converges towards reference solution



Jablonowski and Williamson 2004

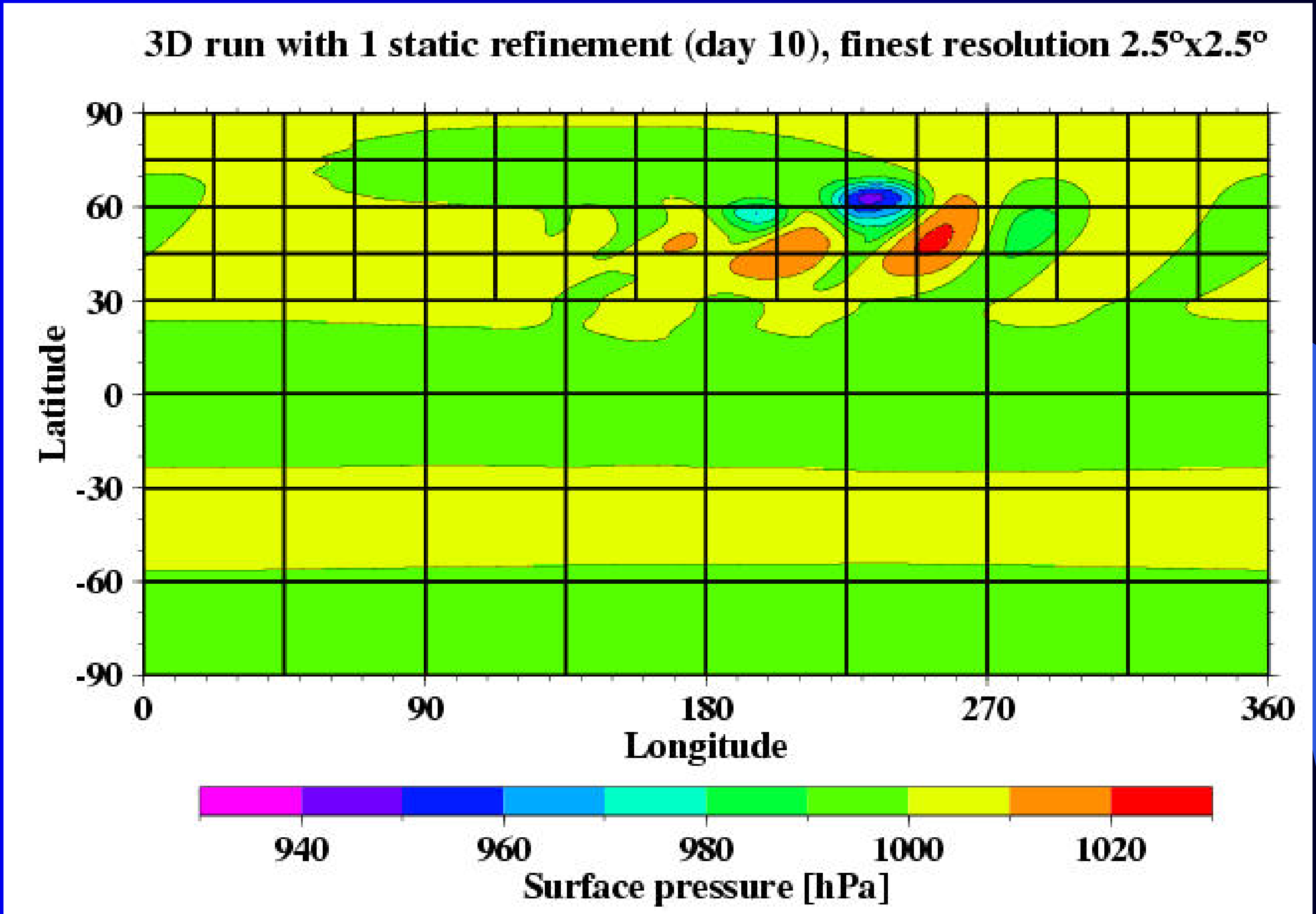
Baroclinic waves in the 3D regime

- Jablonowski-Williamson baroclinic wave test case for dyn. cores
- Coarse resolution does not resolve the wave train



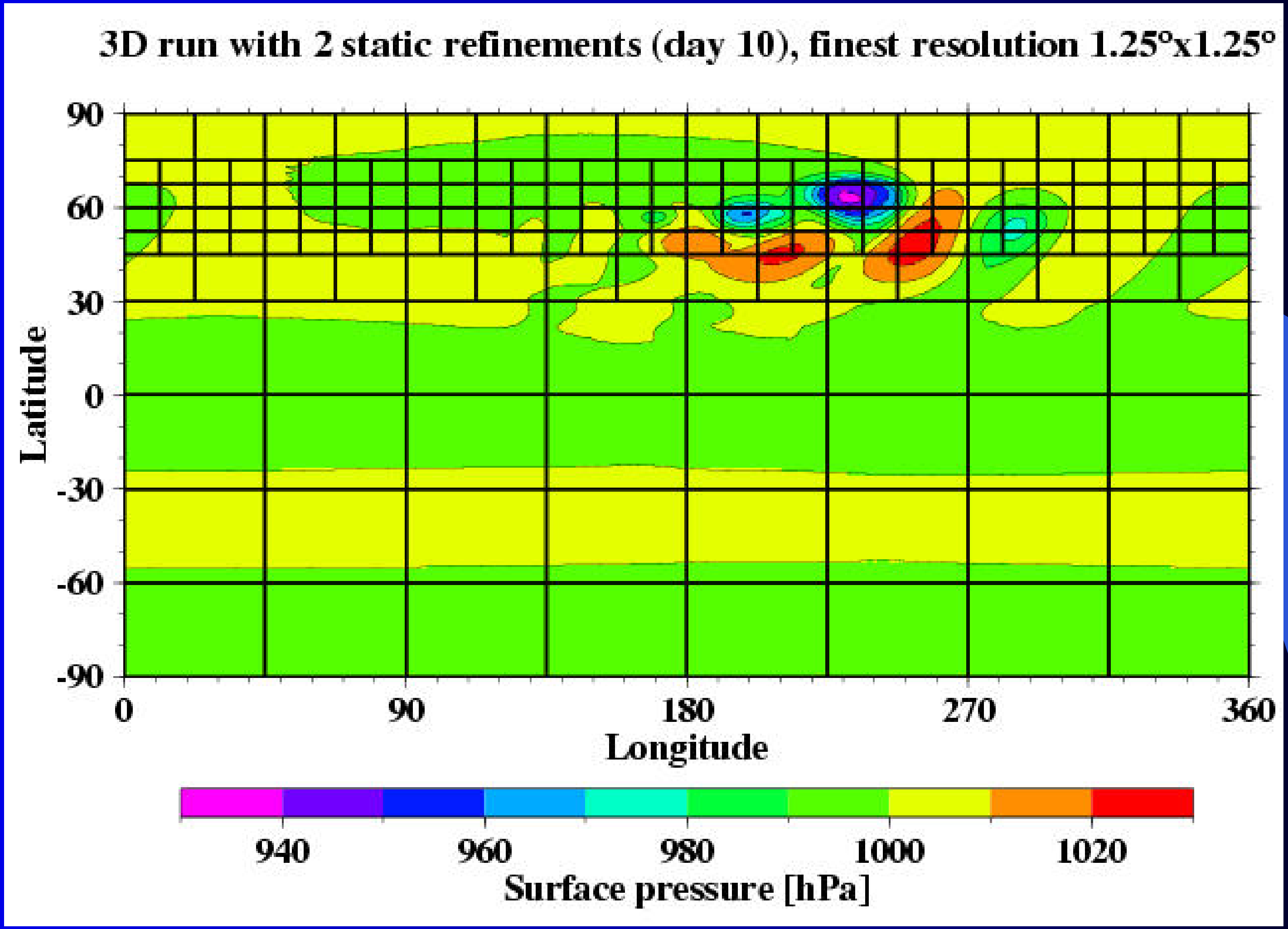
Static adaptations in 3D

- 1 Refinement along the storm track improves the simulation



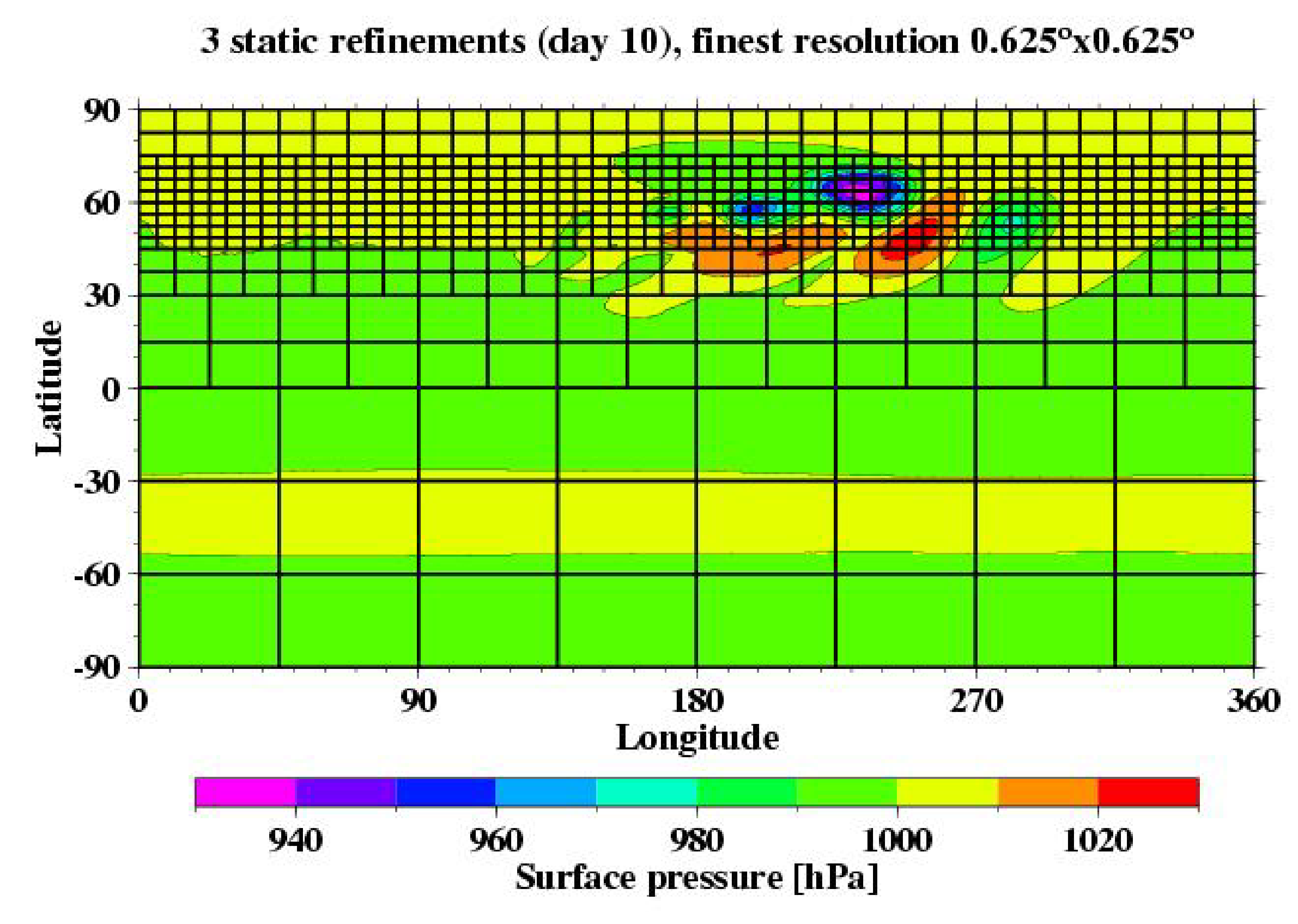
Static adaptations in 3D

- 2 Refinements along the storm track capture the wave accurately



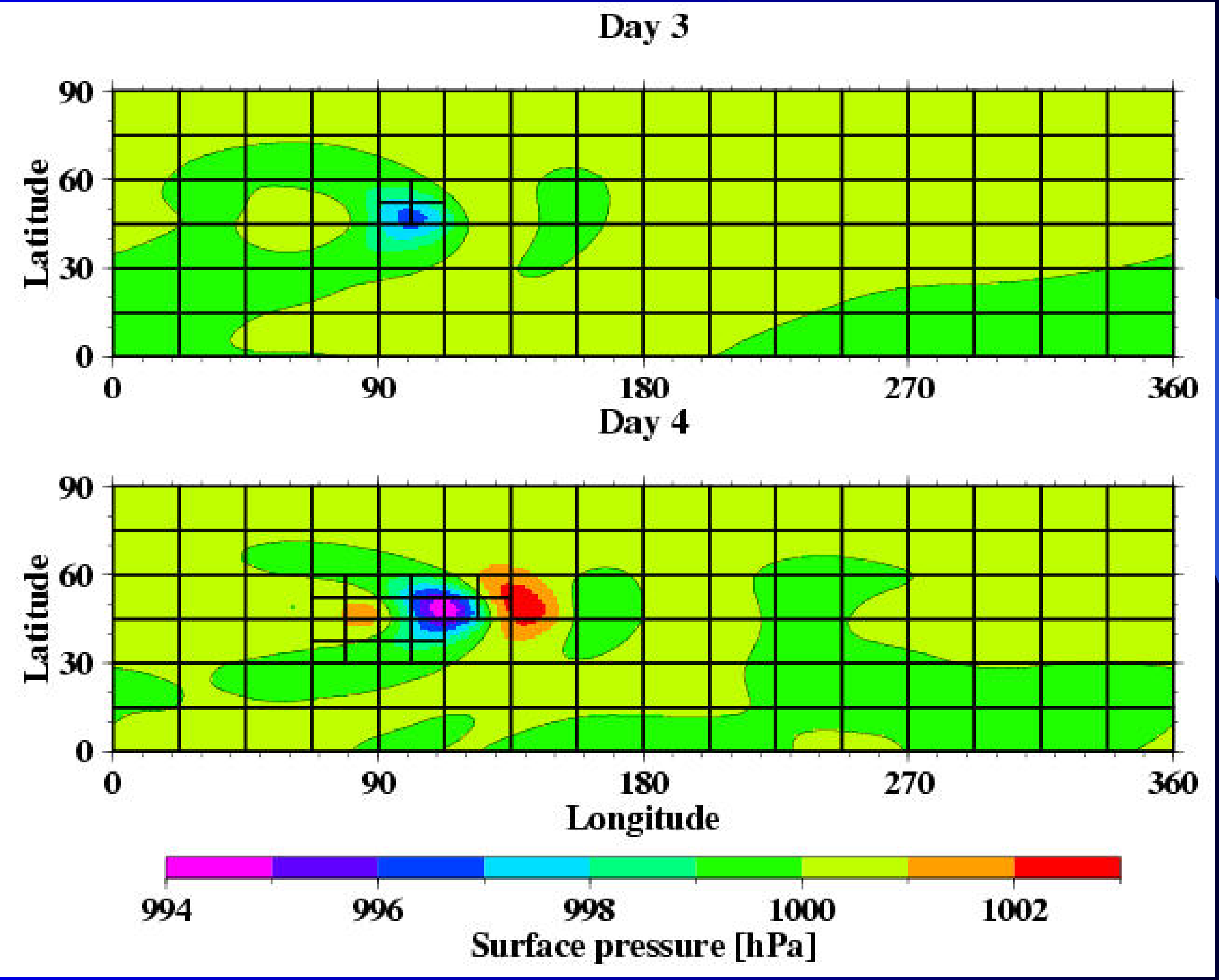
Static adaptations in 3D

- 3 Refinements along the storm track: no further intensification



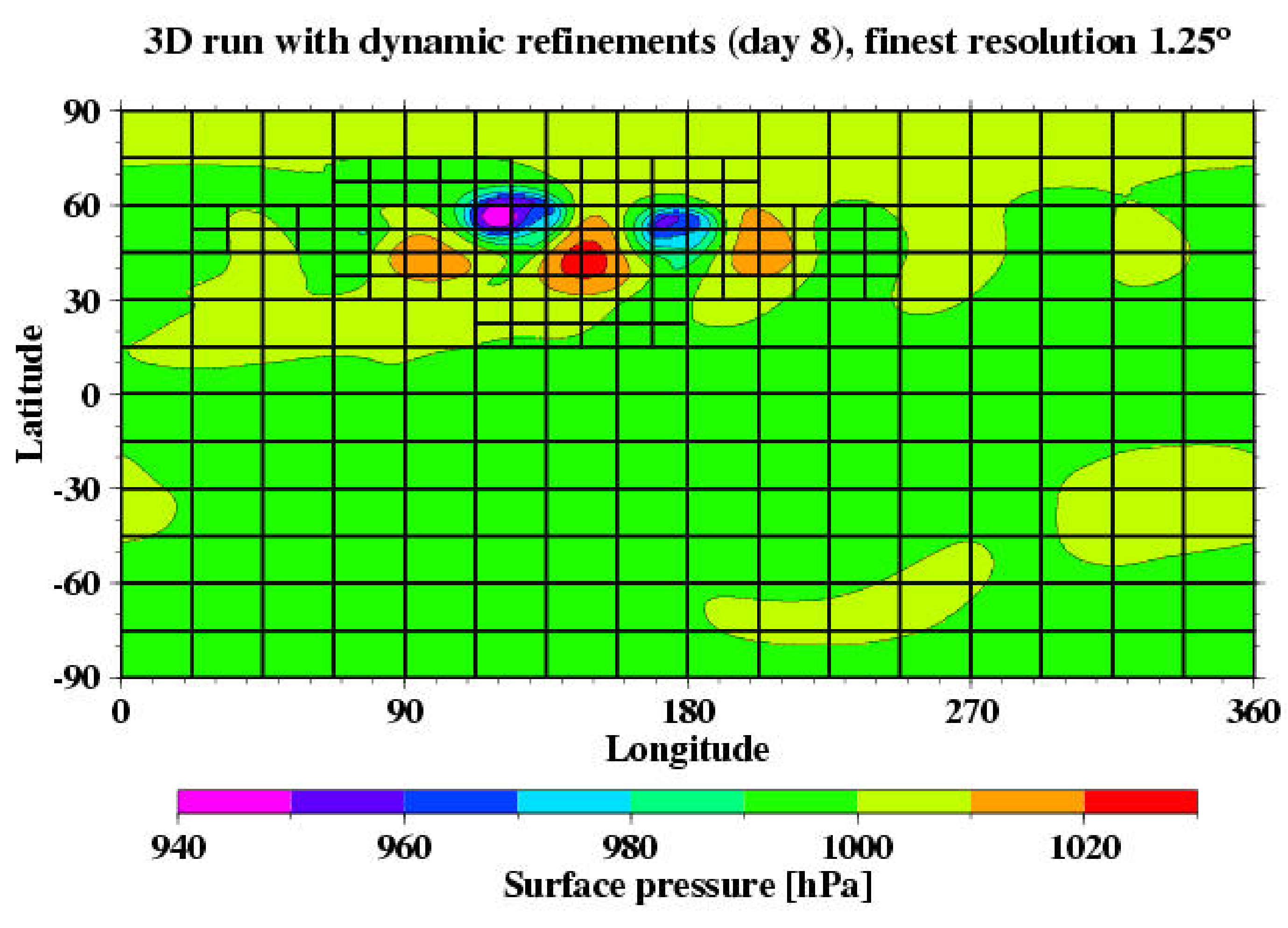
Dynamic adaptations in 3D

- Polvani et al. 2004 baroclinic wave test case
- Refinements are guided by relative vorticity threshold



Dynamic adaptations in 3D

- Baroclinic wave is detected, more accurate prediction
- Sensitive relative vorticity threshold: $0.75*10^{-5}$ 1/s



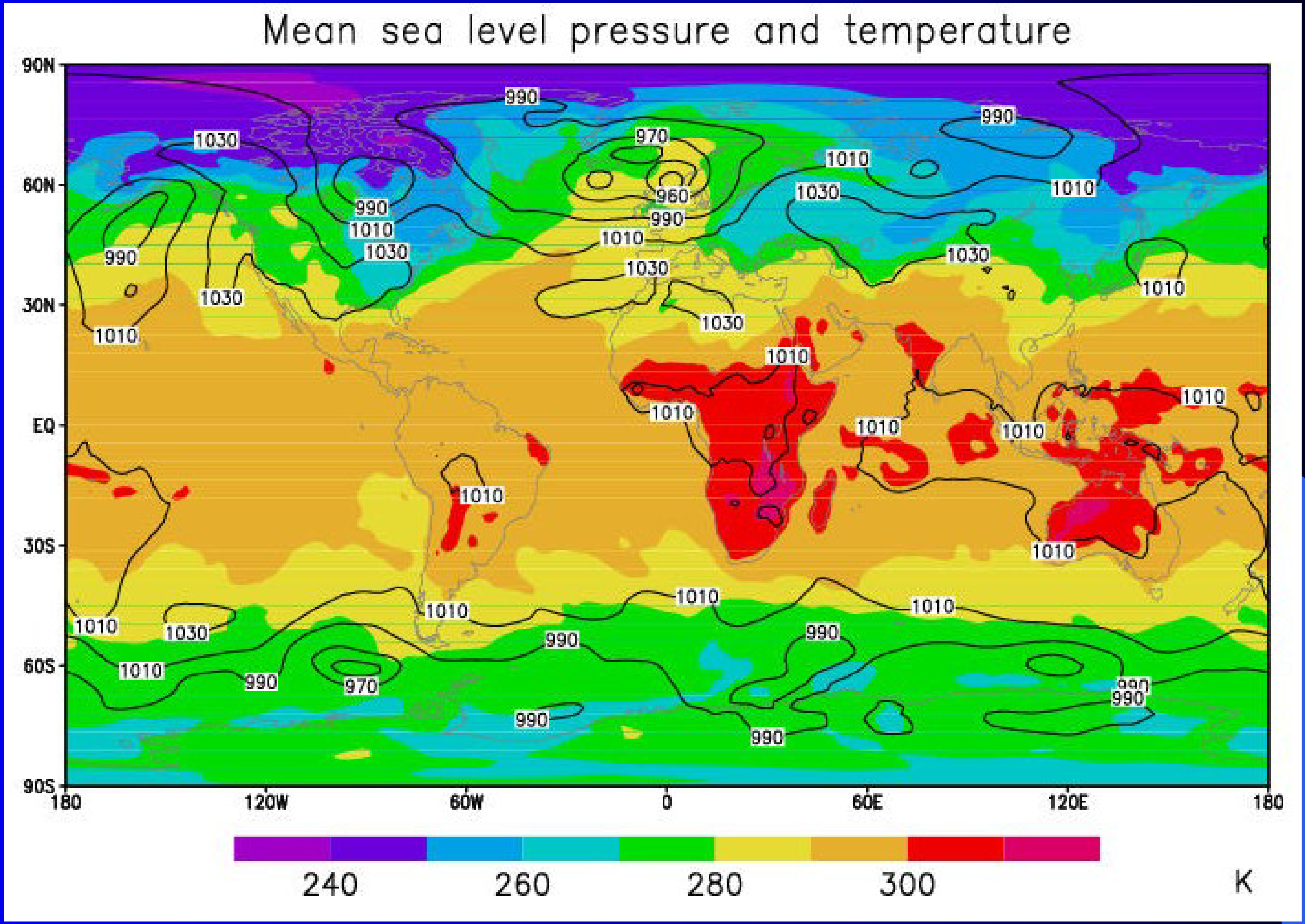
Dynamic adaptation criteria: Features of interest

- Based on flow characteristics:
  - Simple thresholds
  - Gradient: grid is refined in regions with sharp gradients and coarsened in regions with smooth flows
  - Curvature
  - Flow features:
    - Vorticity
    - Divergence
    - Instability indicators, vertical temperature profiles
    - Cloud distribution, tracer concentration, convection, squall lines
- Based on numerics:
  - Estimation of the (numerical) local truncation error

Widely used: flow-based (gradient) indicators, but maybe mix is best

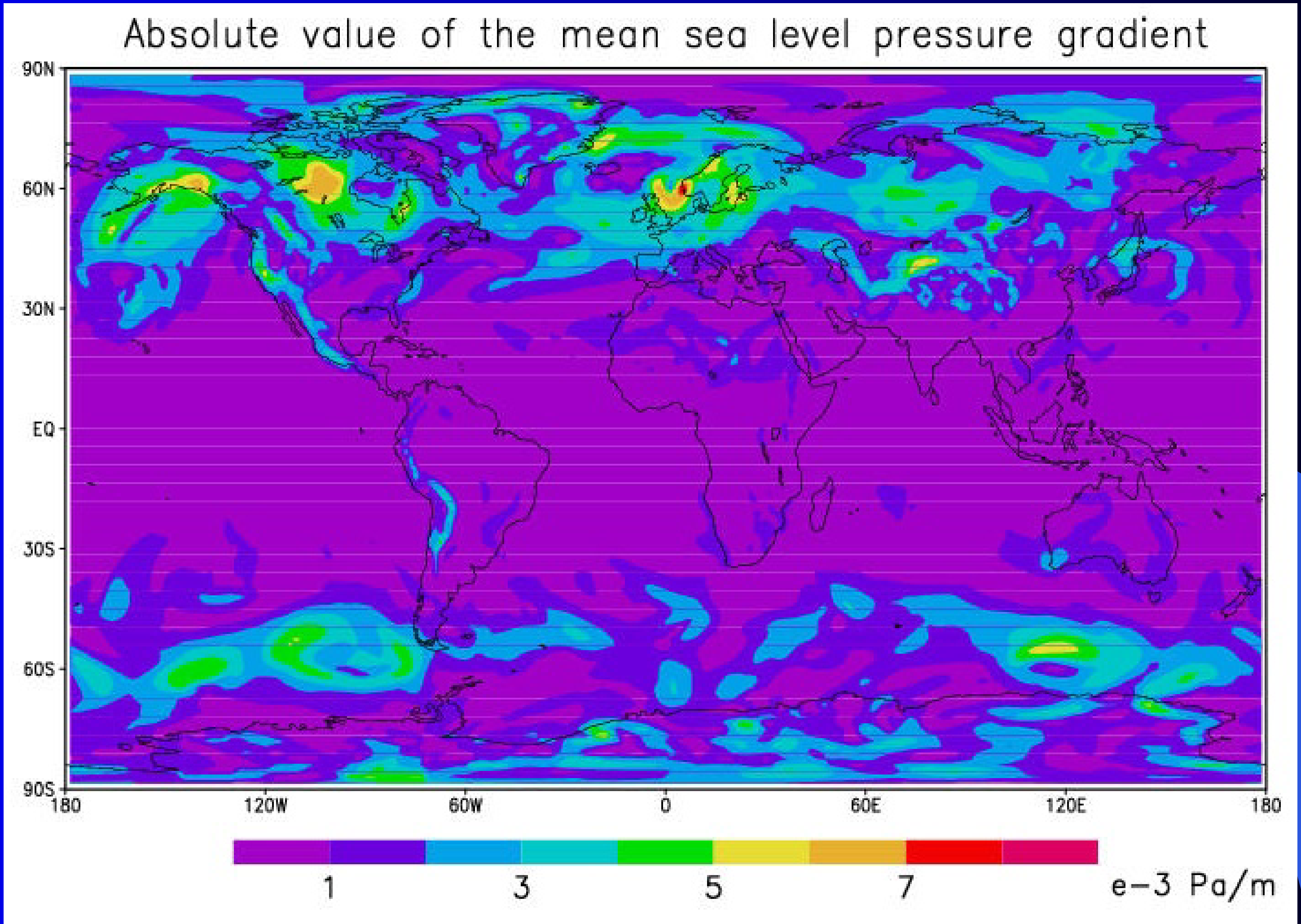
in 3D: vertical level must be selected

Real weather scenarios: 3D regimes



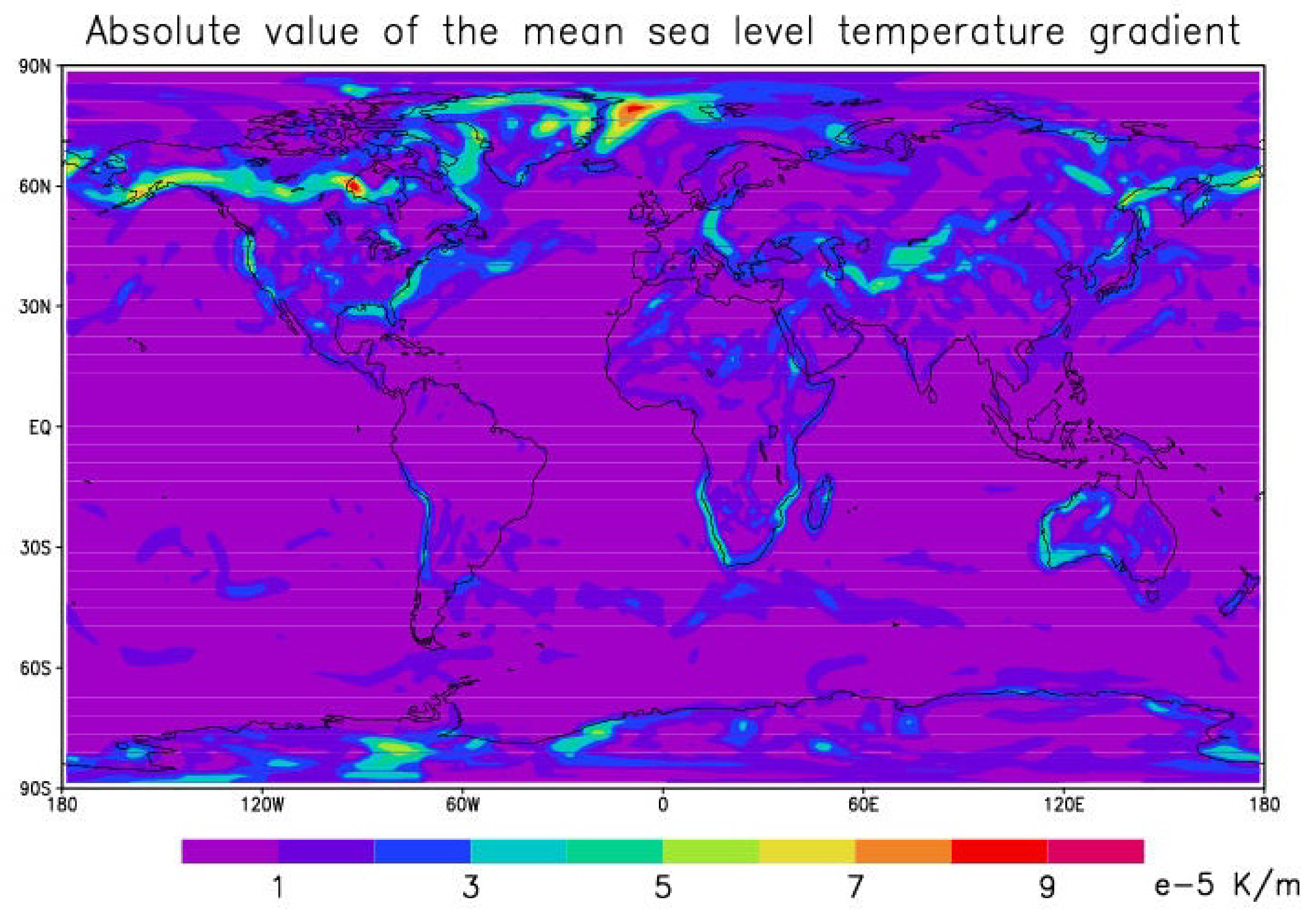
Winter storm in Europe on December 25, 1999

Assessment of possible refinement criteria



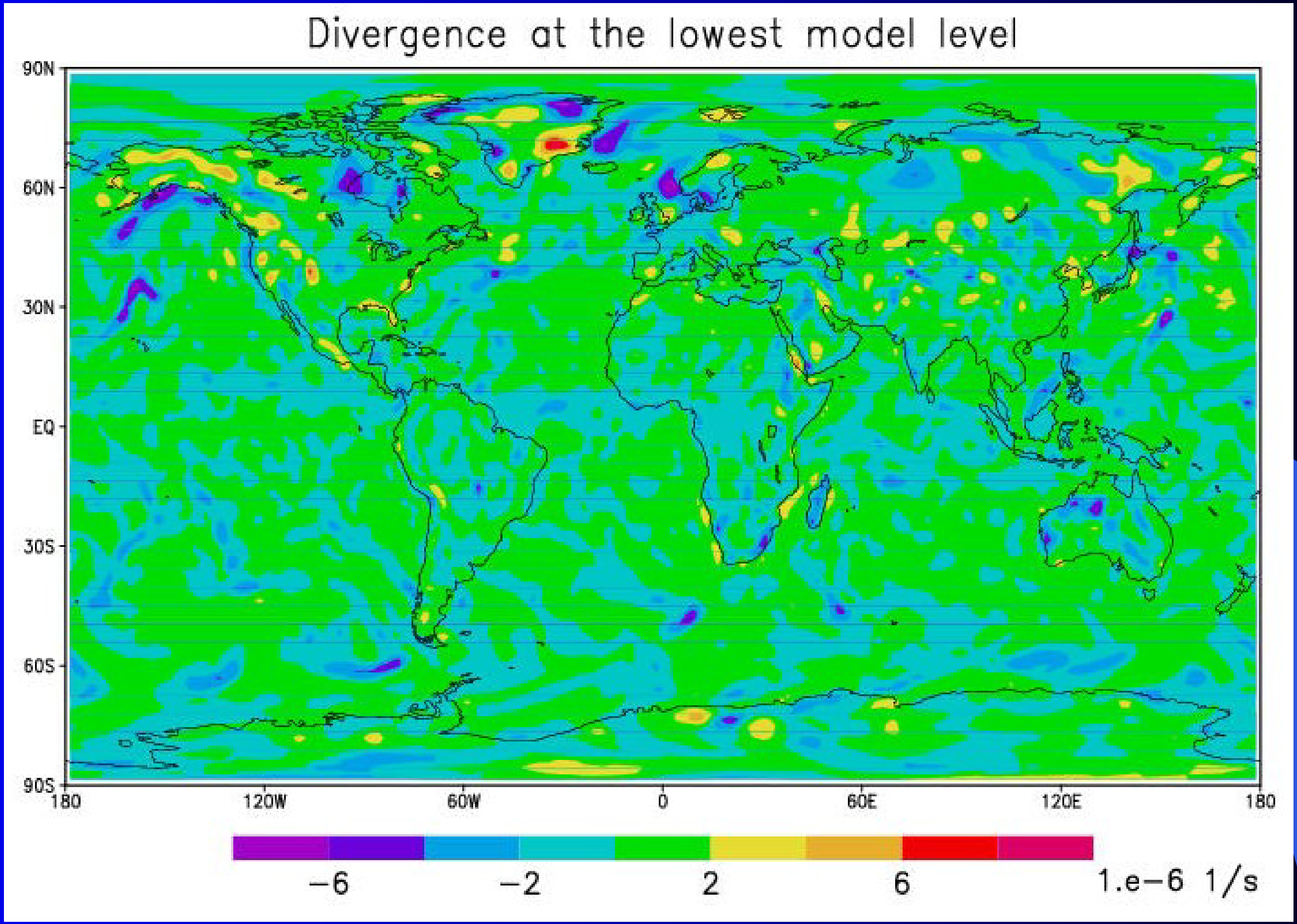
Suitable criterion for baroclinic waves, centers not necessarily detected,
Post-processing quantity

Assessment of possible refinement criteria



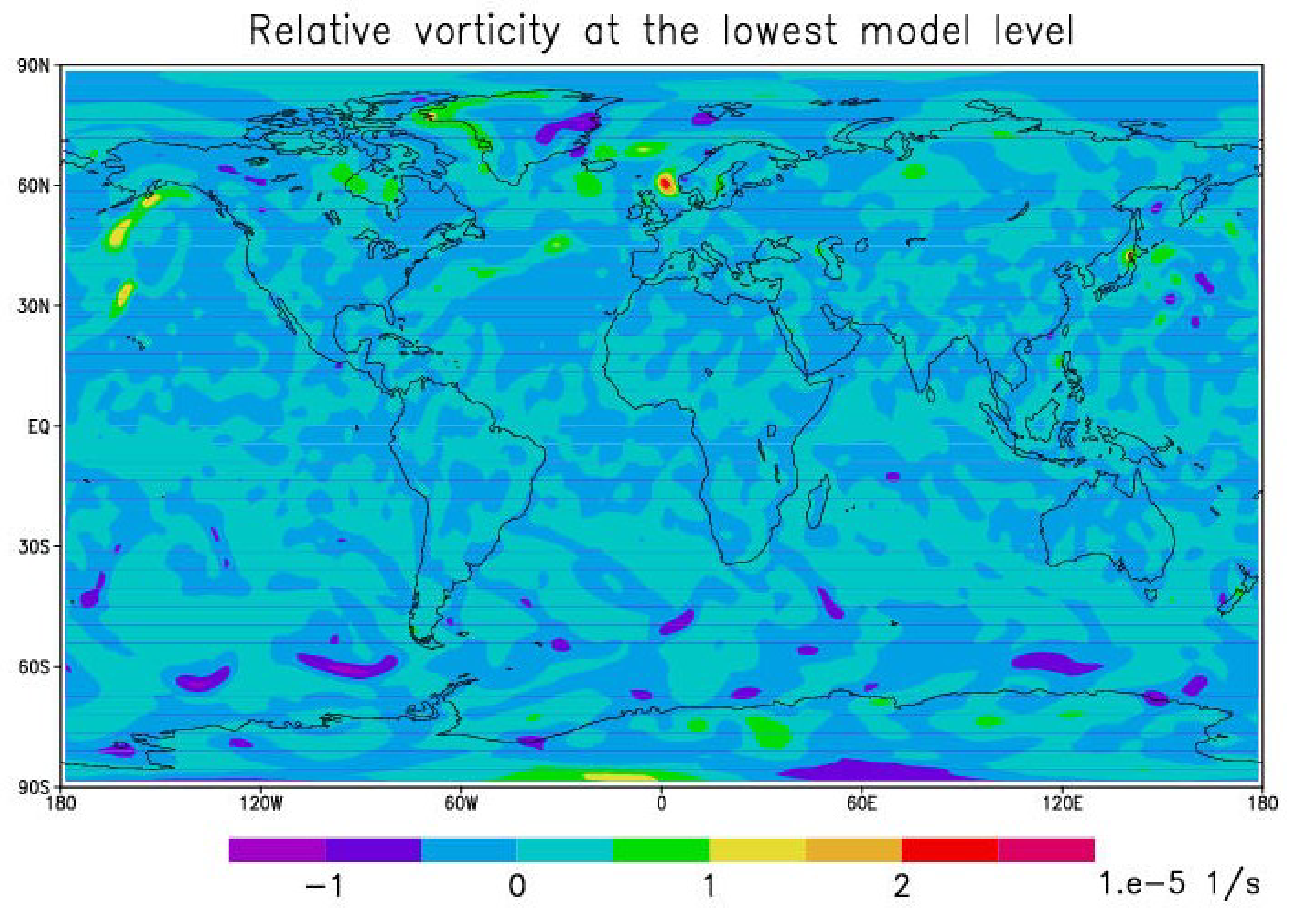
Problematic: also detects land-sea mask, cyclone not detected, post-processing quantity

Assessment of possible refinement criteria



Problematic: Divergence can be noisy

Assessment of possible refinement criteria



Readily available on model levels: Possibly best option
Choice of the vorticity threshold determines the sensitivity

Conclusions

- Static and dynamic refinements on the sphere work
- AMR is a current research topic for the atmospheric sciences
- Future outlook:
  - Static and dynamic adaptations are a viable option for short-term weather predictions
    - ✓ track storms as they appear
    - ✓ focus on forecast region of interest: replace nested grids
  - Static adaptations are feasible for long-term climate studies
    - ✓ refine mountainous terrain, reinitialize orography

⇨ Future steps: Add NCAR's 'physics' package, assess ref. criteria