The ICON project:

Design and performance of an unstructured grid approach for a global triangular grid model

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ICON : ICOsahedral, Nonhdyrostatic model
NWP + Climate + Chemistry

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Outline

- Overview of the ICON development project: motivations and project goals
- Model equations and discretization approach
- Preliminary results of a shallow water model
- Outlook on future work

Desired features for a new model

- Unique framework for large/small scale, lower/upper atmospheric dynamics

- Consistency between discrete tracer advection and discrete continuity equation

- Mass conservative static local grid refinement without spurious interface effects: building block for a multiscale model

Concept of discretization approach

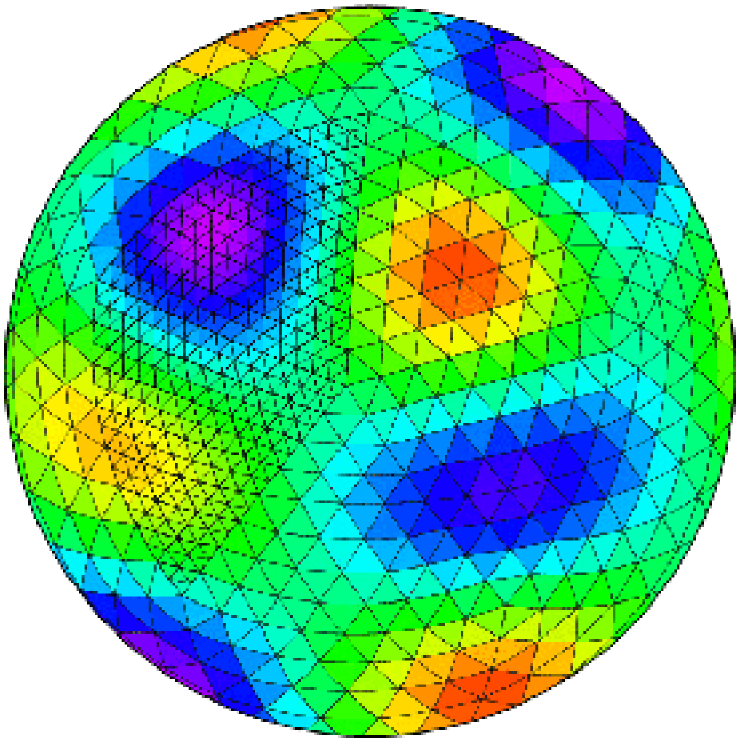
- Achieve the same accuracy and efficiency as advanced NWP models…

- … but preserve some discrete equivalents of global invariants relevant to geophysical flow…

- … and narrow the gap to Computational Fluid Dynamics (CFD) models.

Geodesic icosahedral grids

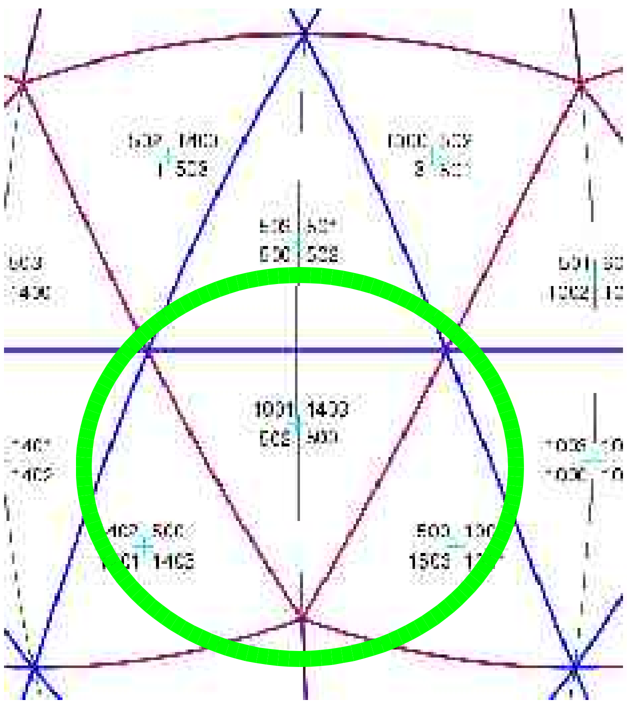
- Special case of Delaunay triangulation
- Solve the pole problem

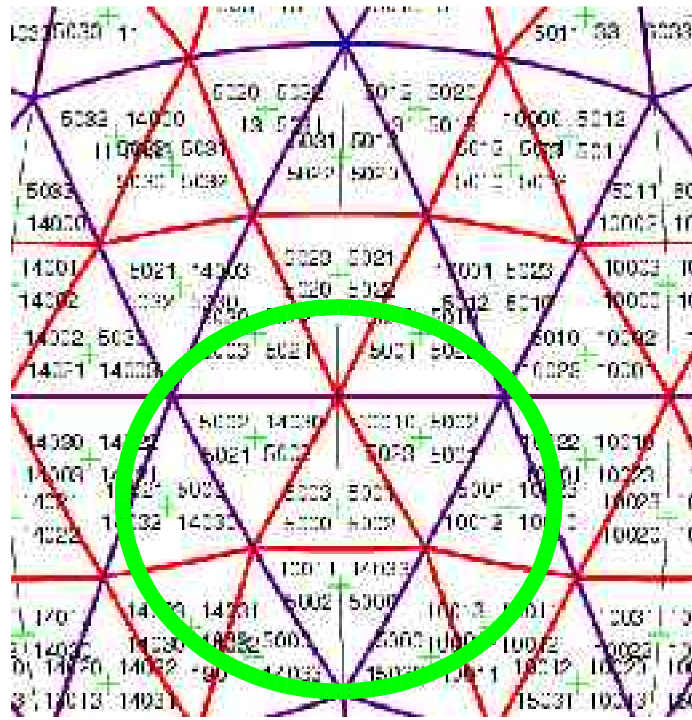


- Local grid refinement
- Multiscale modelling

Implementation issues

Indirect addressing that preserves data locality

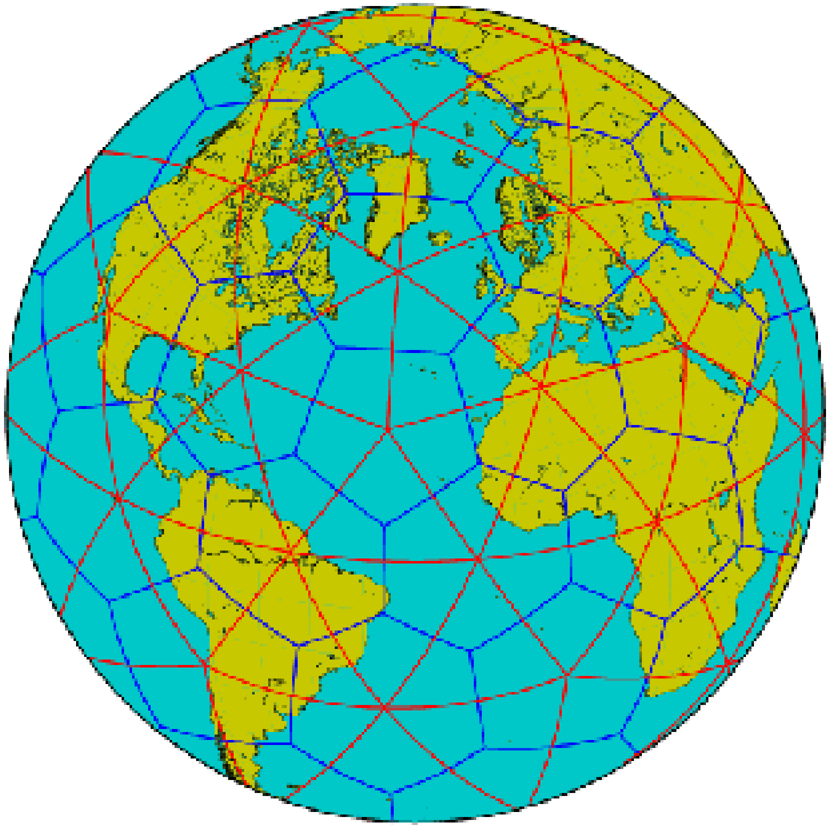




Parallelization: horizontal data decomposition

Spatial discretization

- Finite volume discretization with triangular control volumes: triangular C grid

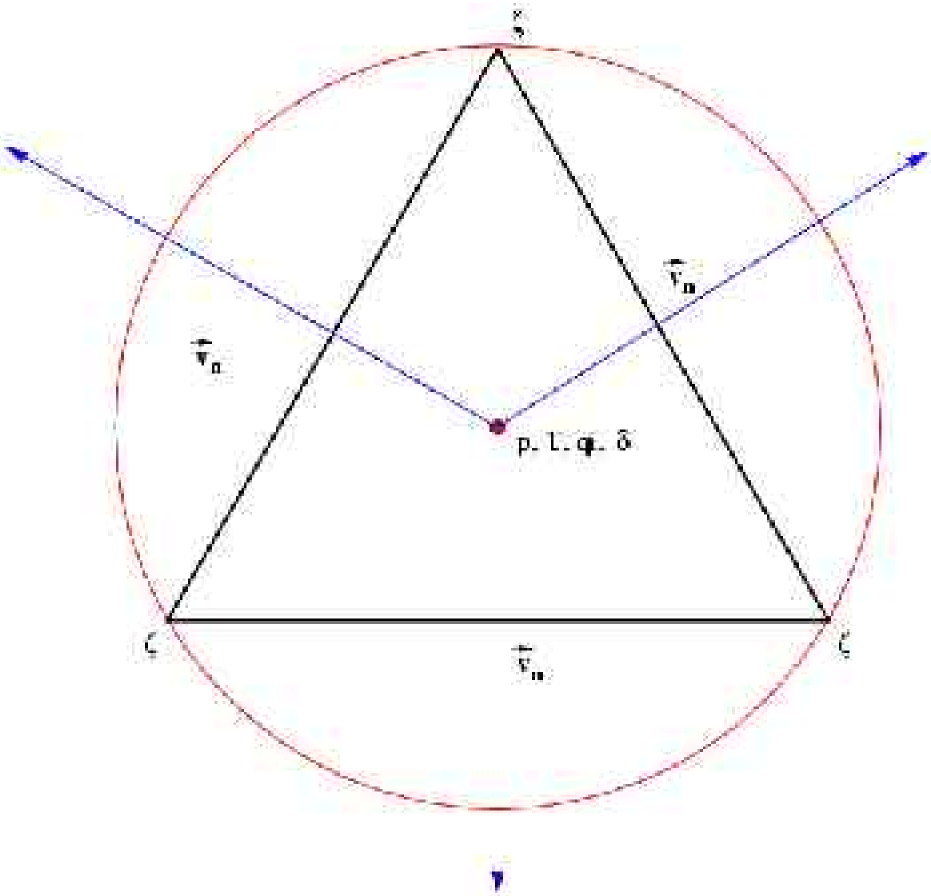


- Delaunay -Voronoi property

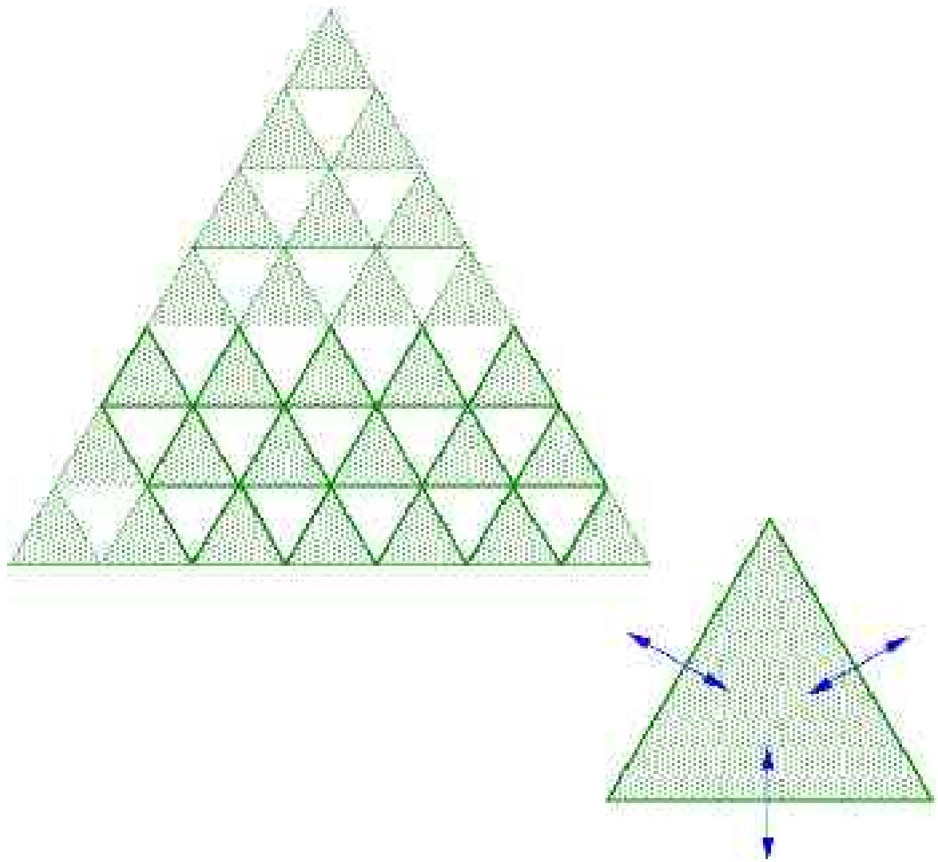
Spatial discretization, properties

- Vorticity at triangle vertices: discrete Helmholtz decomposition (Nicolaides 1992)
- No spurious vorticity production
- Raviart-Thomas reconstruction of velocity, average onto edge for tangential component
- Improve Raviart-Thomas reconstruction by Radial basic functions giving higher order accuracy

The structure of a gridpoint



Some ideas on parallelization



A datastructure

```
TYPE grid_element
  INTEGER :: index
  INTEGER :: parent_index
  INTEGER :: child_index(4)
  INTEGER :: neighbor_index(3)
  TYPE(cartesian_coordinates) :: center
  REAL(dp) :: area
  TYPE(cartesian_coordinates) :: vertex(3)
  TYPE(cartesian_coordinates) :: edge_center(3)
  TYPE(cartesian_coordinates) :: edge_normal(3)
  REAL(dp) :: primal_edge_length(3)
  REAL(dp) :: dual_edge_length(3)
END TYPE grid_element
```

```
TYPE grid
  INTEGER :: level
  TYPE(grid_element), POINTER :: g(:)
END TYPE grid
```

SX-6: 2.2 Gflops for PCG

Cache-based architecures: unusable

... more on data structures

```
INTEGER, ALLOCATABLE :: index(:)
INTEGER, ALLOCATABLE :: parent_index(:)
INTEGER, ALLOCATABLE :: child_index(:,:)

INTEGER, ALLOCATABLE :: neighbor_index(:,:)

REAL(dp), ALLOCATABLE :: area(:)
REAL(dp), ALLOCATABLE :: edge_primal(:,:)
REAL(dp), ALLOCATABLE :: edge_dual(:,:)
REAL(dp), ALLOCATABLE :: center(:,:)

REAL(dp), ALLOCATABLE :: vertex(:,:,:)
REAL(dp), ALLOCATABLE :: edge_center(:,:,:)
REAL(dp), ALLOCATABLE :: edge_normal(:,:,:)
```

Acceptable solution:
but not well structured

... even more on data structures

```
TYPE triangle
  TYPE(triangle), POINTER  :: parent
  TYPE(triangle), POINTER  :: sub_triangle0 => NULL()
  TYPE(triangle), POINTER  :: sub_triangle1 => NULL()
  TYPE(triangle), POINTER  :: sub_triangle2 => NULL()
  TYPE(triangle), POINTER  :: sub_triangle3 => NULL()
  TYPE(triangle), POINTER  :: neighbor0 => NULL()
  TYPE(triangle), POINTER  :: neighbor1 => NULL()
  TYPE(triangle), POINTER  :: neighbor2 => NULL()
  TYPE(edge), POINTER :: edge0 => NULL()
  TYPE(edge), POINTER :: edge1 => NULL()
  TYPE(edge), POINTER :: edge2 => NULL()
  TYPE(vertex), POINTER :: vertex0 => NULL()
  TYPE(vertex), POINTER :: vertex1 => NULL()
  TYPE(vertex), POINTER :: vertex2 => NULL()
END TYPE triangle
```

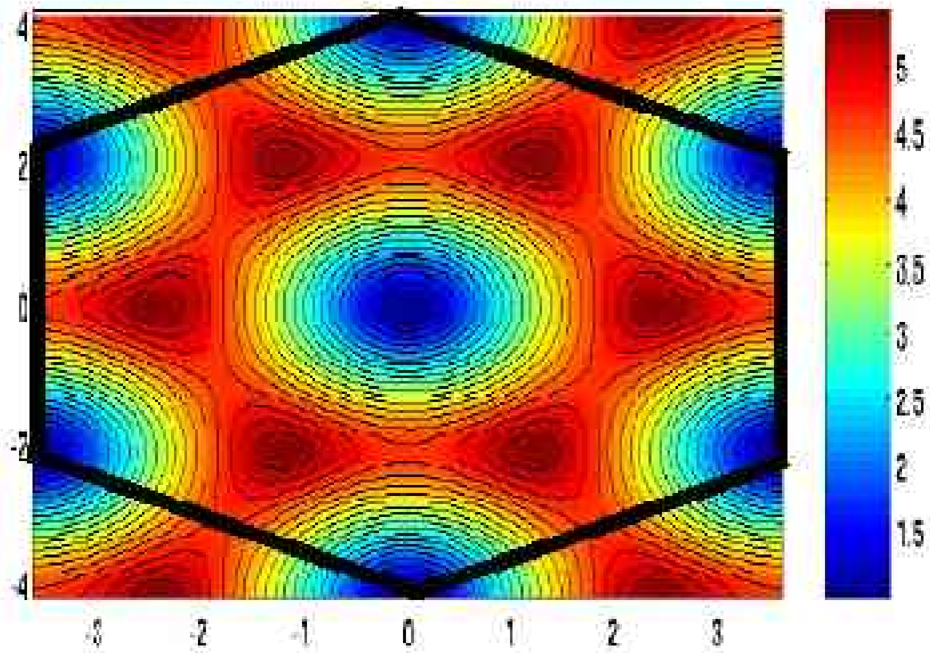
Topological point of view

Discrete wave dispersion analysis

- Stationary geostrophic solution, no spurious pressure modes
- Two physical gravity wave modes
- Two spurious gravity wave modes: frequencies always higher than physical ones

$$\omega^2 = \frac{8\,gH}{d^2} \pm \frac{8\,gH}{3\,d^2}\sqrt{1+4\cos^2\left(\frac{\sqrt{3}}{2}kd\right)+4\cos\left(\frac{\sqrt{3}}{2}kd\right)\sin(}$$

Dispersion plot, physical mode



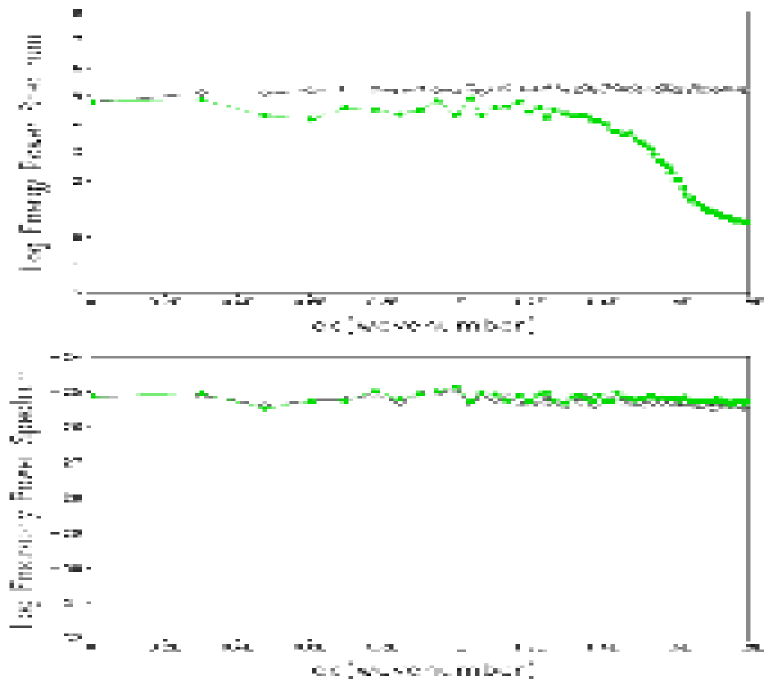
- Less good wavenumber space than quadrilateral C-grid
- Zero group velocity at high wavenumbers

Discrete global invariants

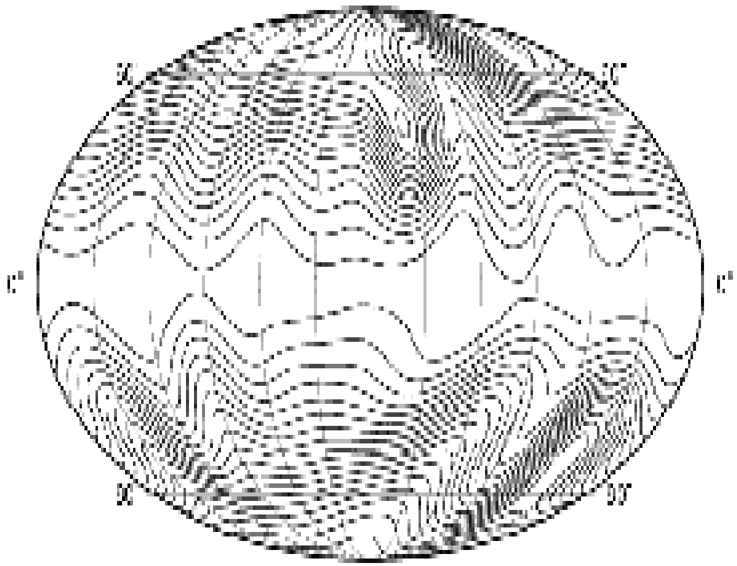
- Mass conservation, consistent discretizations of continuity equation and tracer transport
- Mass and potential vorticity conservation, no spurious vorticity production
- Potential enstrophy conserving variant
- Energy conserving variant: Sadourny, JAS 1975

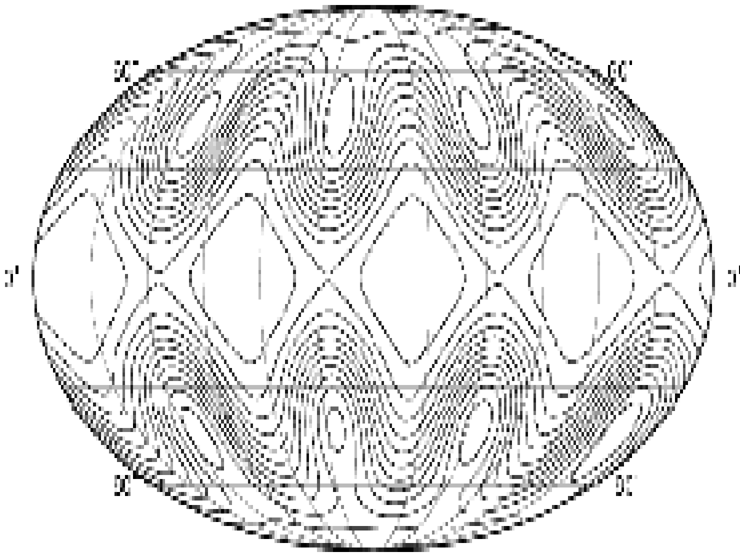
Random initial data on rotating plane (1000 days)

Relative vorticity after 1000 days integration with random initial data (numerical test carried out by Todd Ringler, CSU)

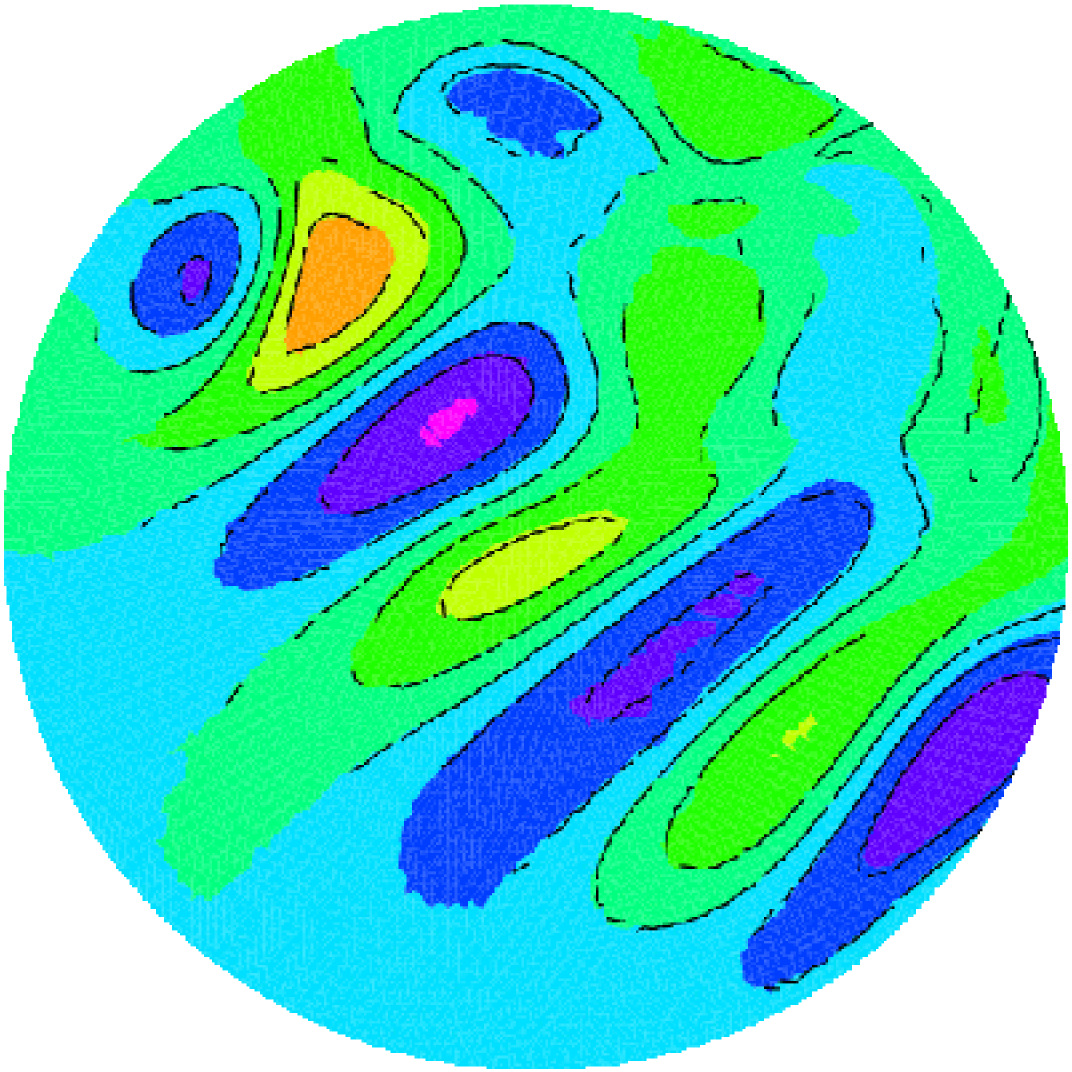


Shallow water test cases: tests 5-6





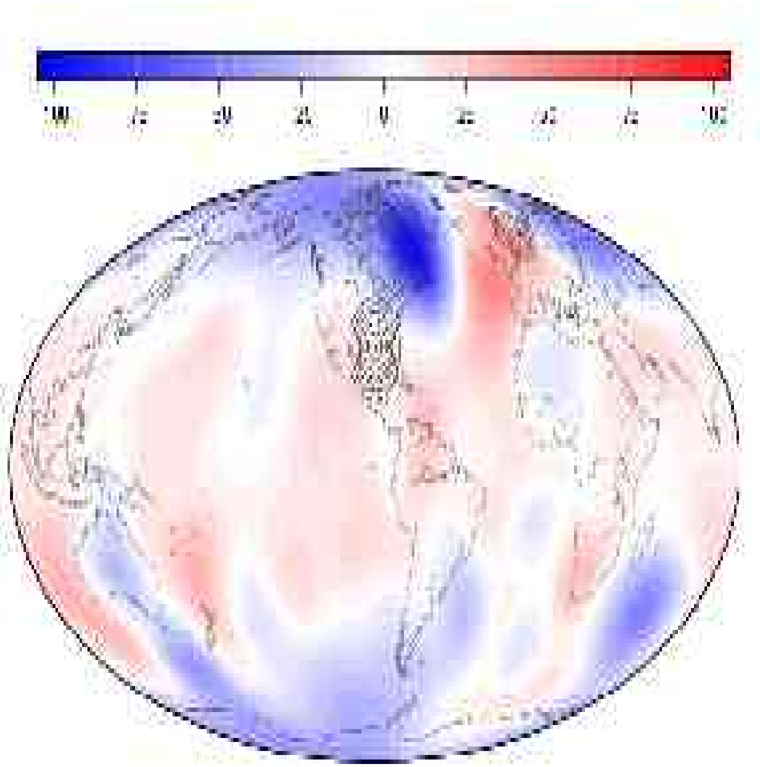
Test case 5
Relative vorticity
day 10



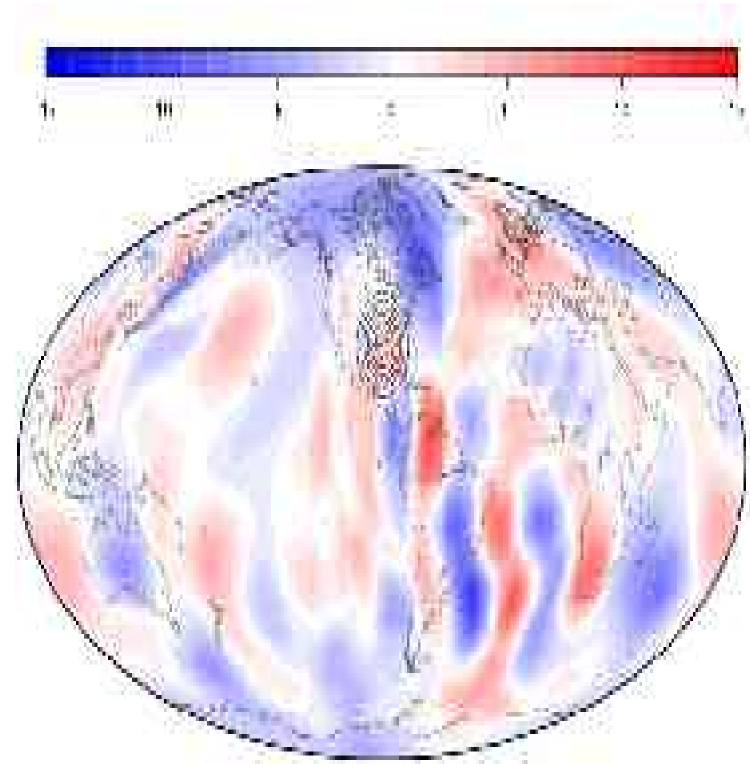
Colour shading:
model results

Black contours:
NCAR reference
spectral model

Test 5, height field error at day 15



Glevel 6, dt = 900 s

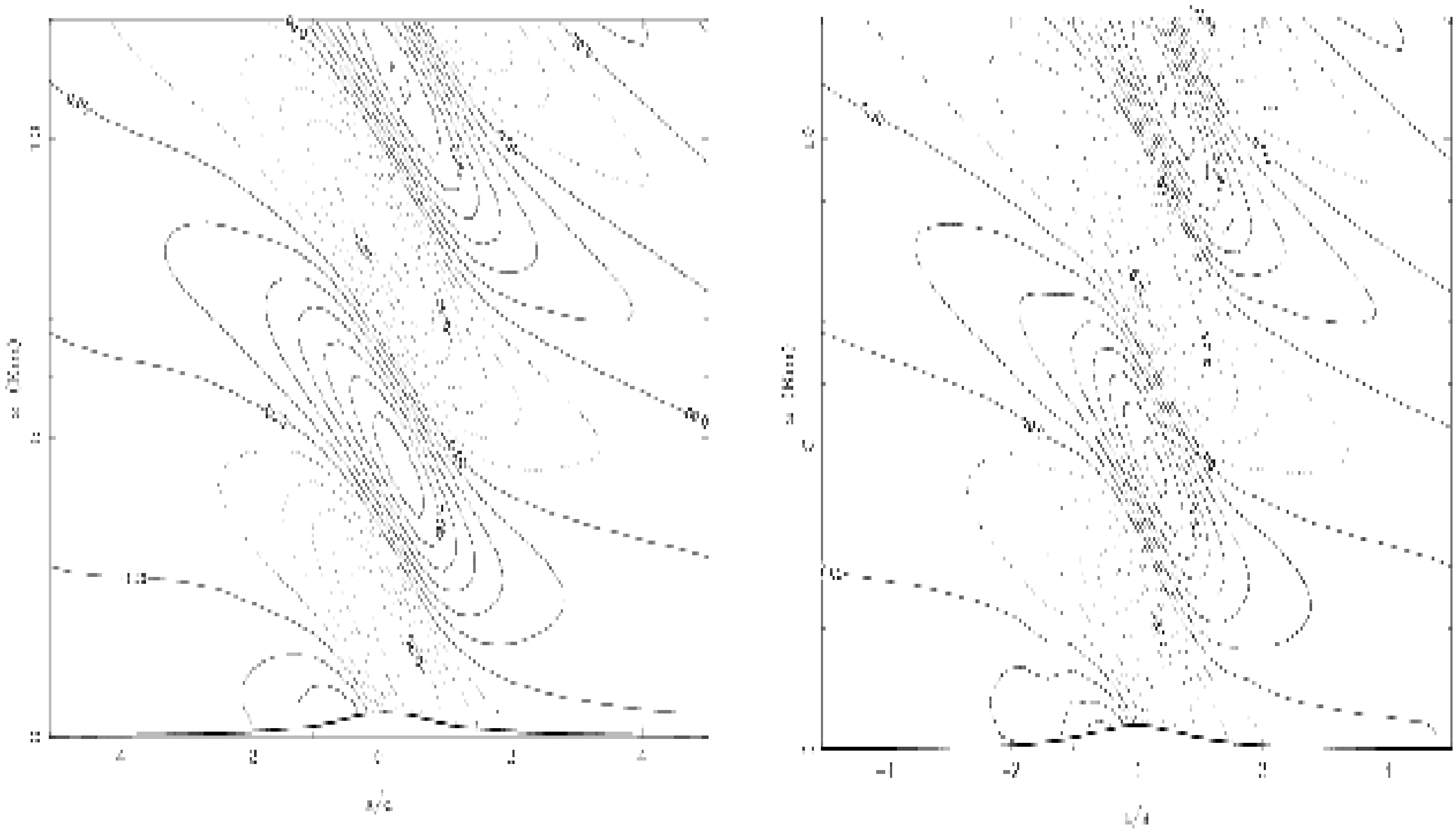


Glevel 7, dt = 90 s

Some options for vertical coordinates

- Hybrid pressure vertical coordinate + new horizontal discretization: preliminary 3d-ICON model
- Terrain following normalized height coordinate + new horizontal discretization: first choice for operational, global nonhydrostatic model
- Non normalized, geometric height coordinate + cut cells

Geometric height + cut cells



Outlook

- Optimized data structure and parallelization for model on locally refined grids
- Hydrostatic, 3D model on locally refined grids
- Coupling to existing MPI physics package, impact of spurious modes on simulations with full physics
- Sensitivity of results to local refinement