ECMWF 2004 SEMINAR
Recent Developments in Numerical Methods for Atmospheric and Ocean Modelling
6 to 10 September 2004

Max-Planck-Institut für Meteorologie
Max Planck Institute for Meteorology

The ICON project: development of a unified model using triangular geodesic grids

DWD

Max-Planck-Institut für Meteorologie
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An Institute of the Max Planck Society

ICON: ICOsahedral grid, Nonhdyrostatic unified (NWP+ climate+chemistry) model

- **ICON development team:**

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- **Discussions and/or joint work: N.Botta, F. Giraldo, J.Klemp, R.Klein, D.LeRoux, D.Randall, T.Ringler, H.Tomita**

Outline

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

Desired features for a new model

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

- **Consistency between conservative discrete tracer advection and continuity equation**

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

Concept of discretization approach

- Achieve the same **accuracy** and **efficiency** of advanced **NWP** models…

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

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

Nonhydrostatic, compressible flow

$$\frac{\partial \rho}{\partial t} + \nabla \bullet (\rho \mathbf{u}) = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + \boldsymbol{\eta} \times \mathbf{u} = -\nabla K - \frac{1}{\rho} \nabla p - \nabla \Phi$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \bullet \left[(\rho \varepsilon + p) \mathbf{u} \right] = -\nabla \bullet \mathbf{R}$$

Shallow water flow

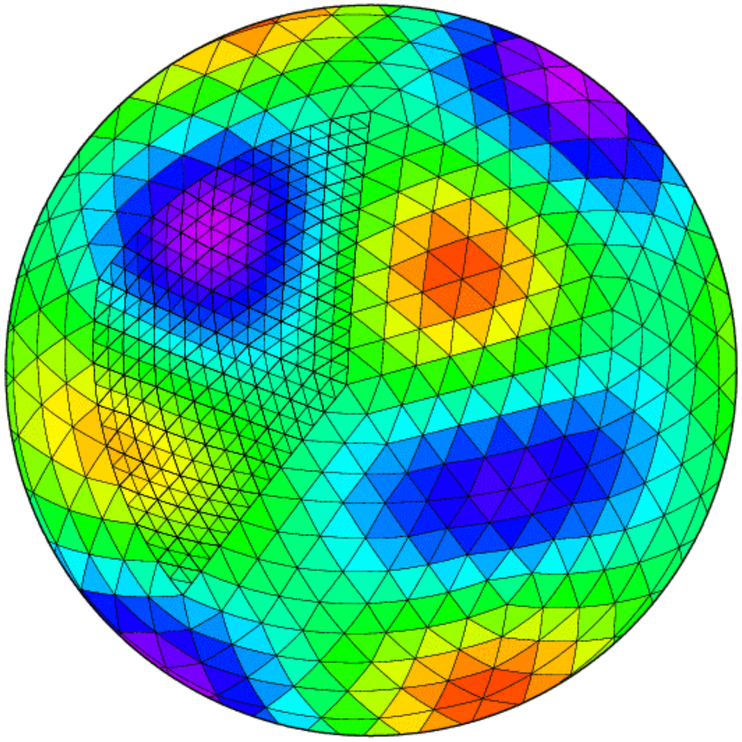
$$\frac{\partial h}{\partial t} + \nabla \bullet (H\mathbf{u}) = 0$$

$$\frac{\partial \mathbf{u}}{\partial t} + (\zeta + f)\mathbf{k} \times \mathbf{u} + \nabla(gh + K) = 0$$

$$\frac{\partial (cH)}{\partial t} + \nabla \bullet (cH\mathbf{u}) = 0$$

Geodesic icosahedral grids

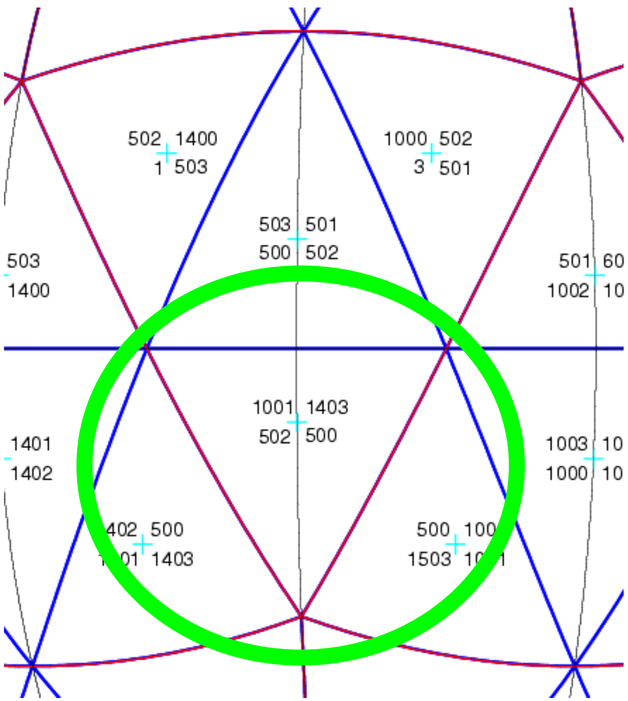
- Solve the pole problem
- Special case of Delaunay triangulation

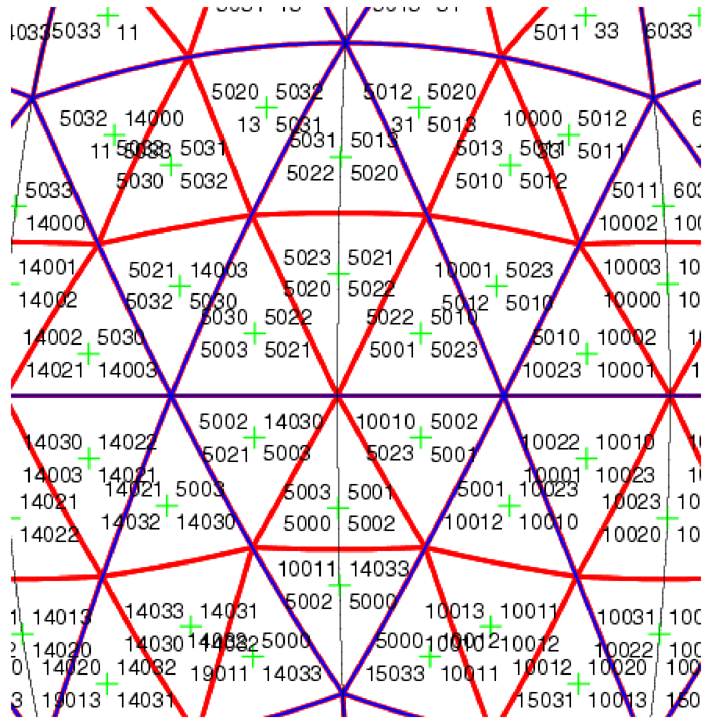


- Local grid refinement
- Multiscale modelling

Data structures for grid representation

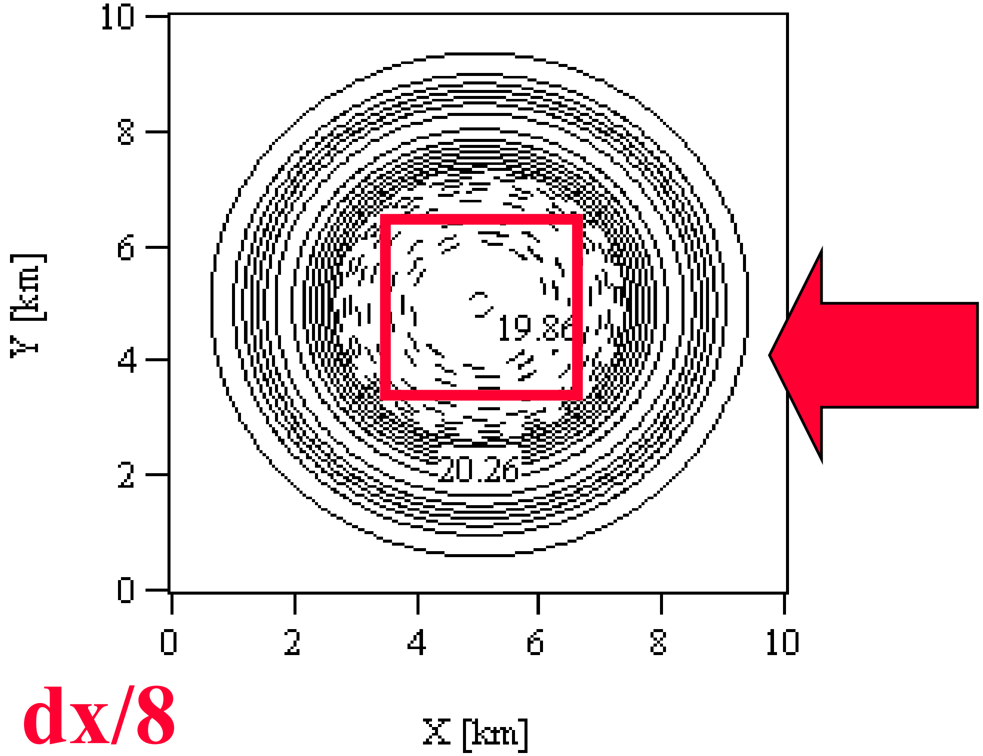
Indirect addressing that preserves data locality



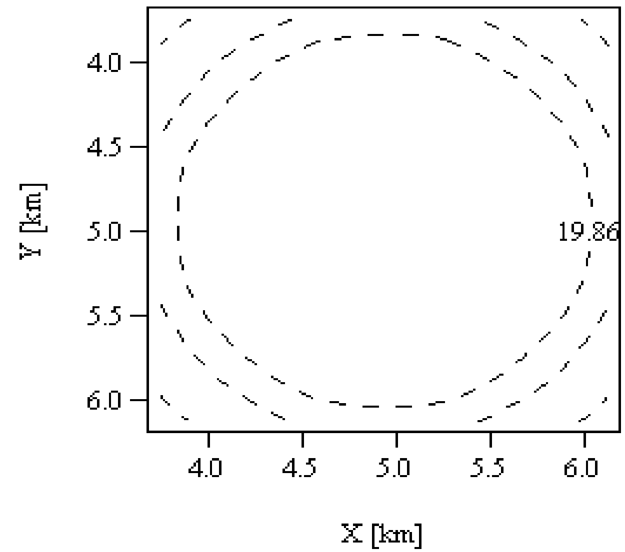


Parallelization: horizontal data decomposition

Consistent fluxes at coarse/fine interface



dx/8

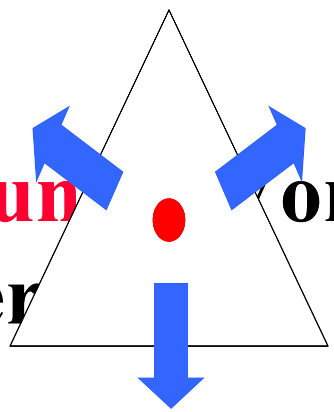


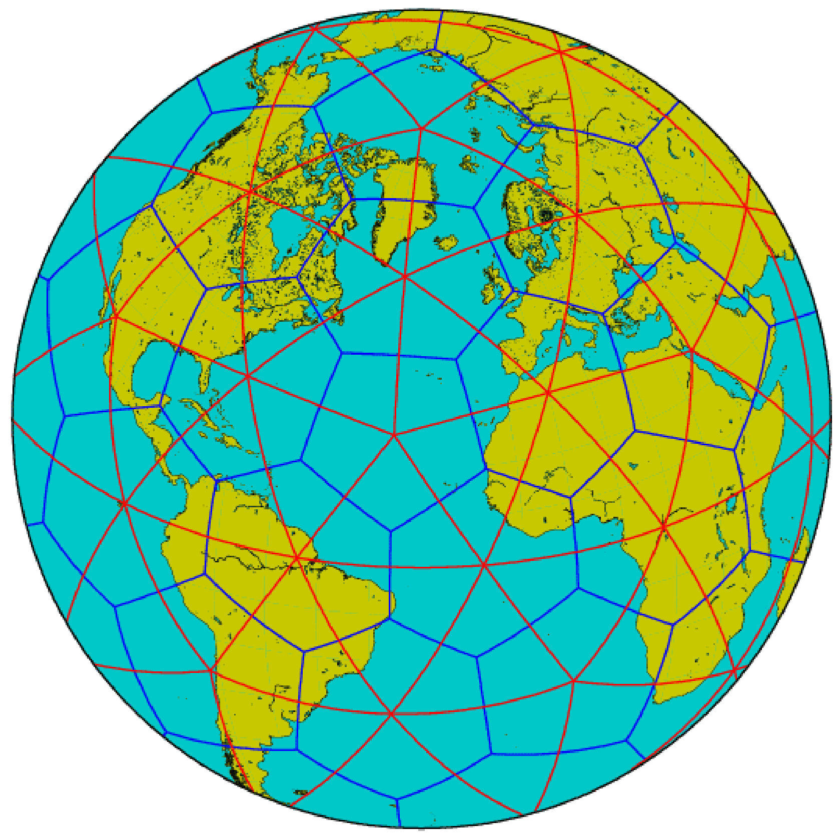
dx/4

Edwards JCP 1996, Bornemann and Deuflhard Num.Math.1996, B. and Rosatti, IJNMF 2002

Spatial discretization

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

- **Delaun**  **oronoi proper**



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

$$\mathbf{u}(\mathbf{x}) = \mathbf{u}_0 + \alpha \mathbf{x}$$

Discrete shallow water system

$$\frac{\partial h_i}{\partial t} = -\sum_{l \in C(i)} u_l H_l \sigma_{i,l}$$

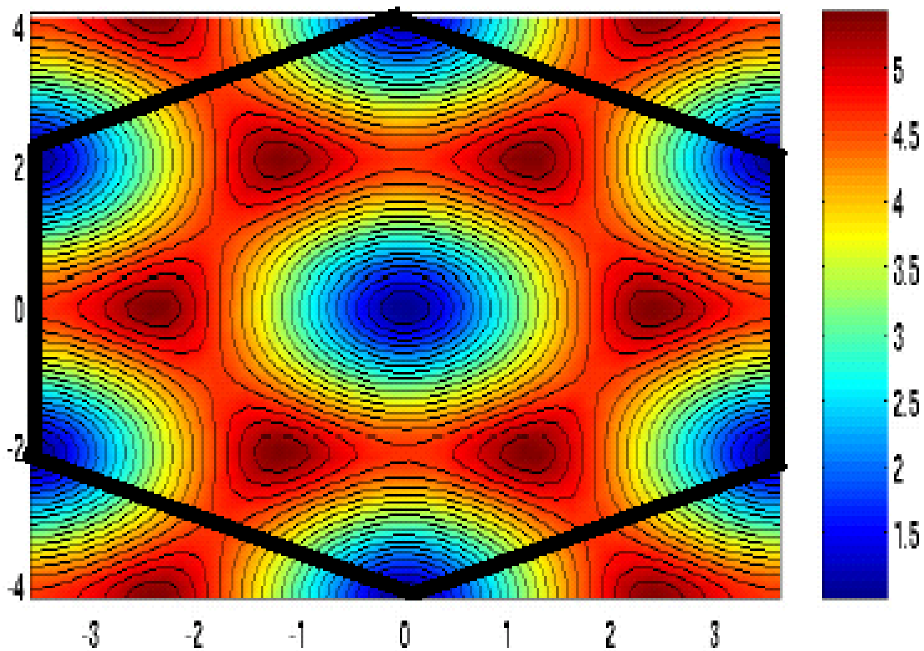
$$\frac{\partial u_l}{\partial t} = -(\zeta + f)_l v_l - \delta_v (K + gh)_l$$

$$\frac{\partial (c_i H_i)}{\partial t} = -\sum_{l \in C(i)} c_l u_l H_l \sigma_{i,l}$$

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

Dispersion plot, physical mode



- **Less good** **wavenumber space than quad C**
- **Zero group velocity** **at high wavenumbers**

Discrete global invariants

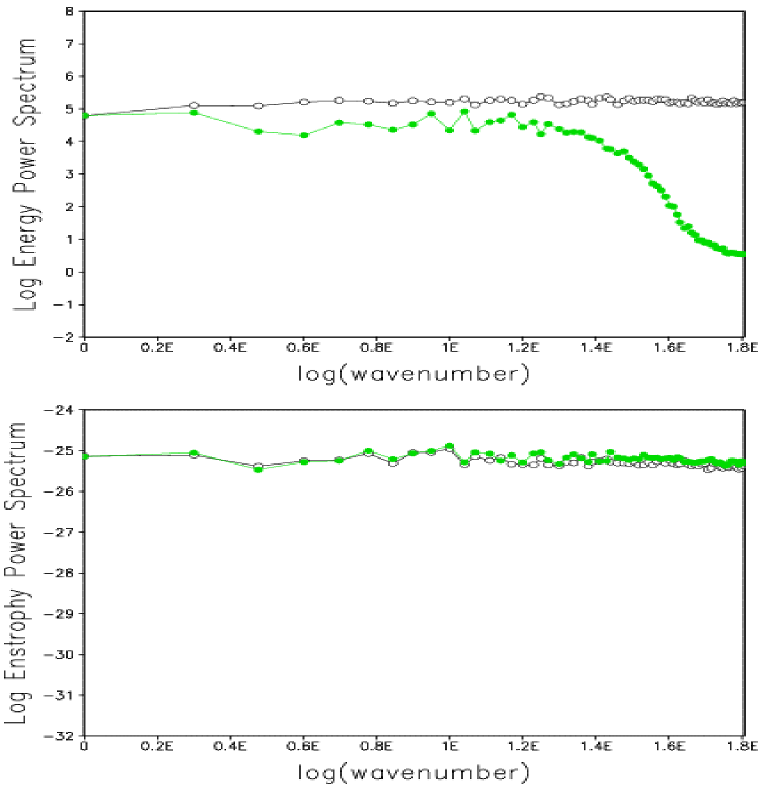
- Mass conservation, consistent discretizations of continuity equation and tracer transport

- Potential vorticity conservation, no spurious vorticity production

- Potential enstrophy conserving variant, energy conserving variant: Sadourny JAS 1975

Random initial data, f plane

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

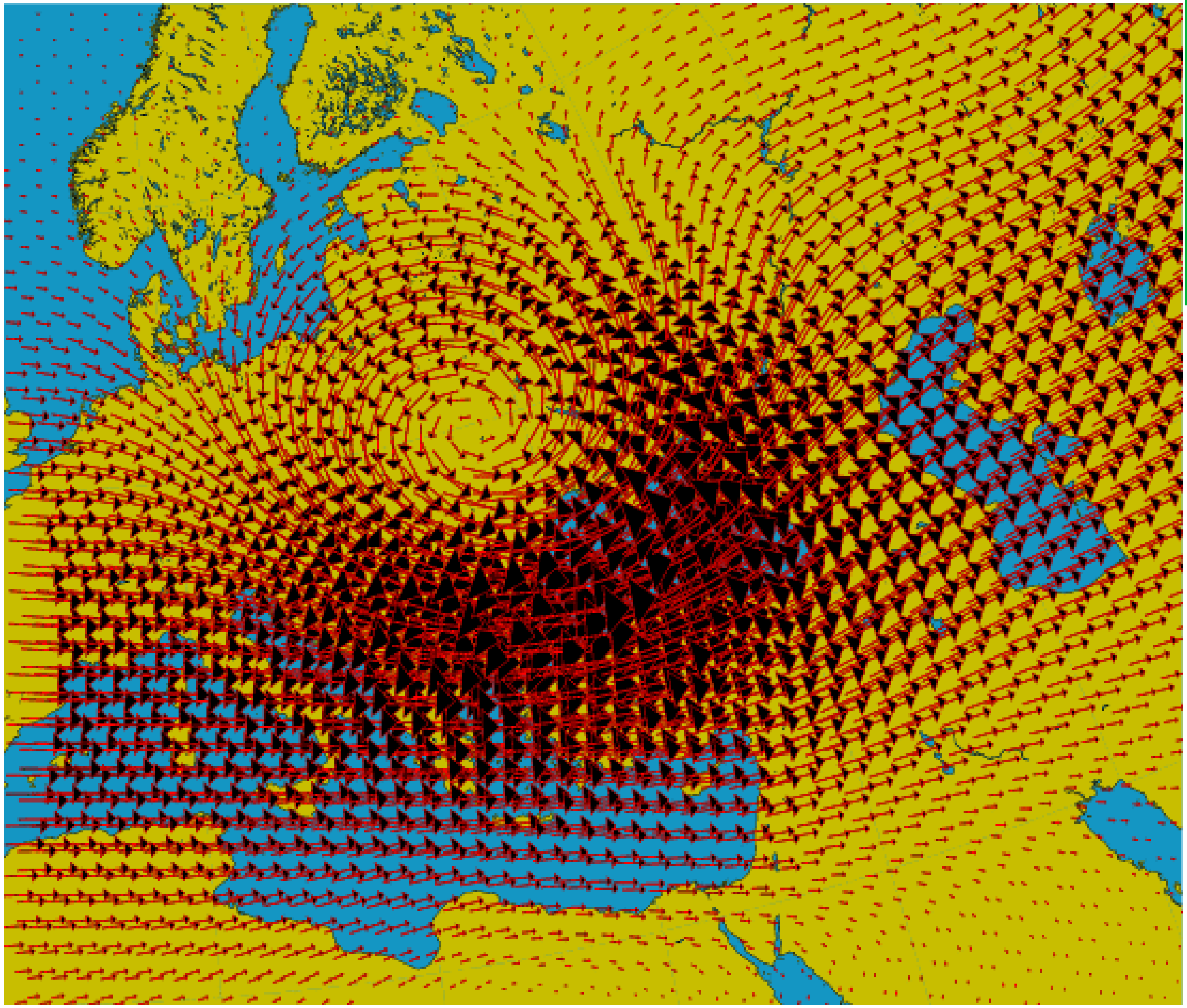


Semi-implicit time discretization

$$u_l^{n+1} = u_l^n - \Delta t(\widetilde{\zeta}^{\,n+1/2} + f)_l v_l^{n+1/2} - \Delta t \delta_v (\widetilde{K}^{n+1/2} + gh^{n+1/2})_l$$

$$h_i^{n+1} = h_i^n - \Delta t \sum_{l \in C(i)} u_l^{n+1/2} H_l^n \sigma_{i,l}$$

Idealized vortex, day 2

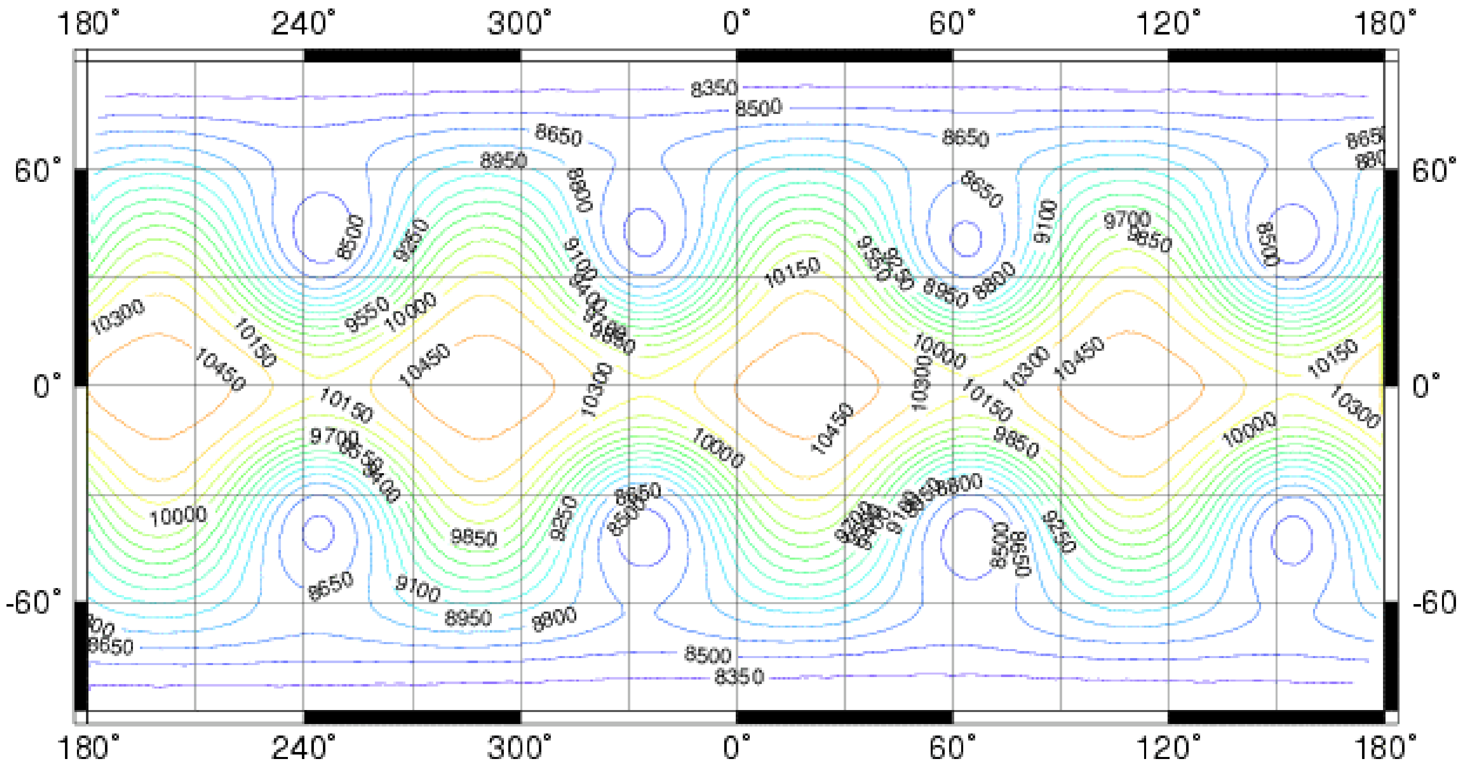


Maximum resolution 40 km

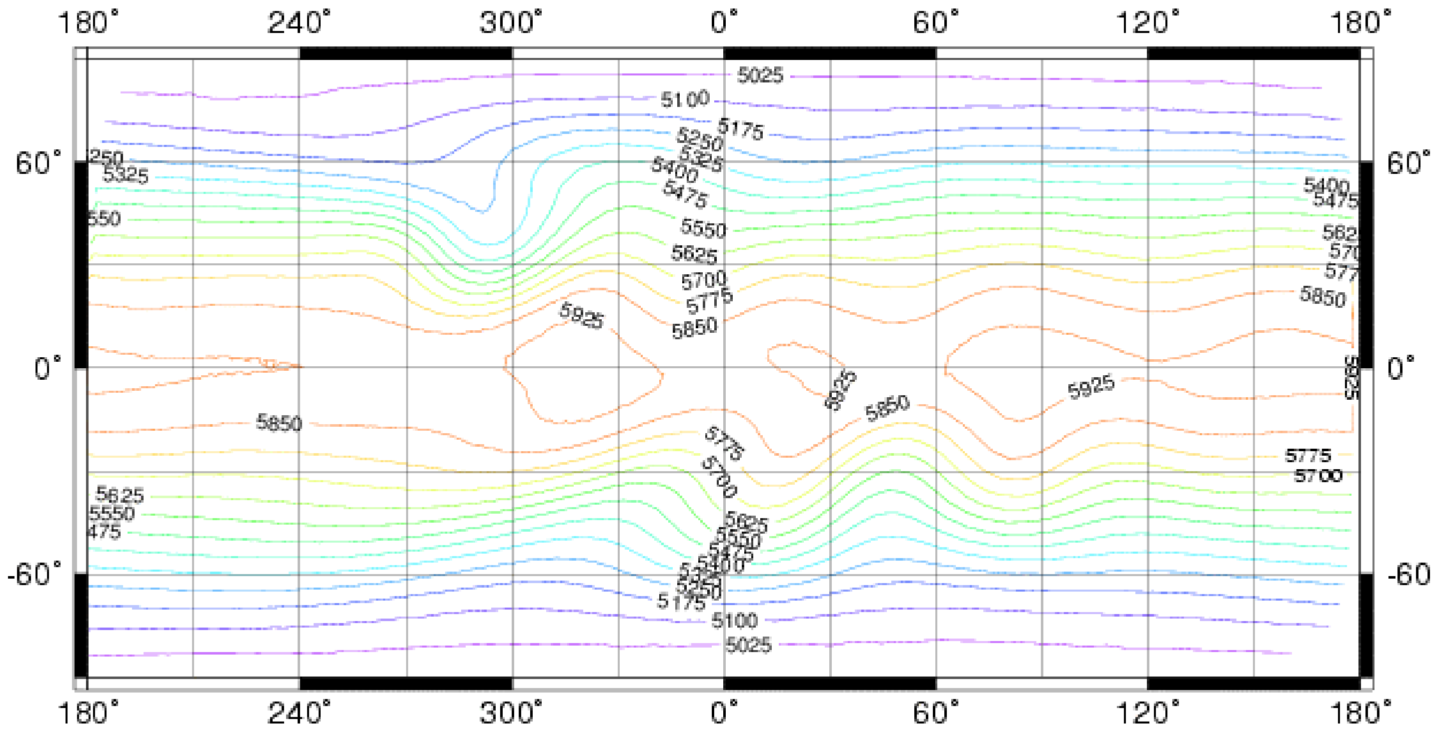
Maximum gravity wave Courant number 7

(dt=900 s)

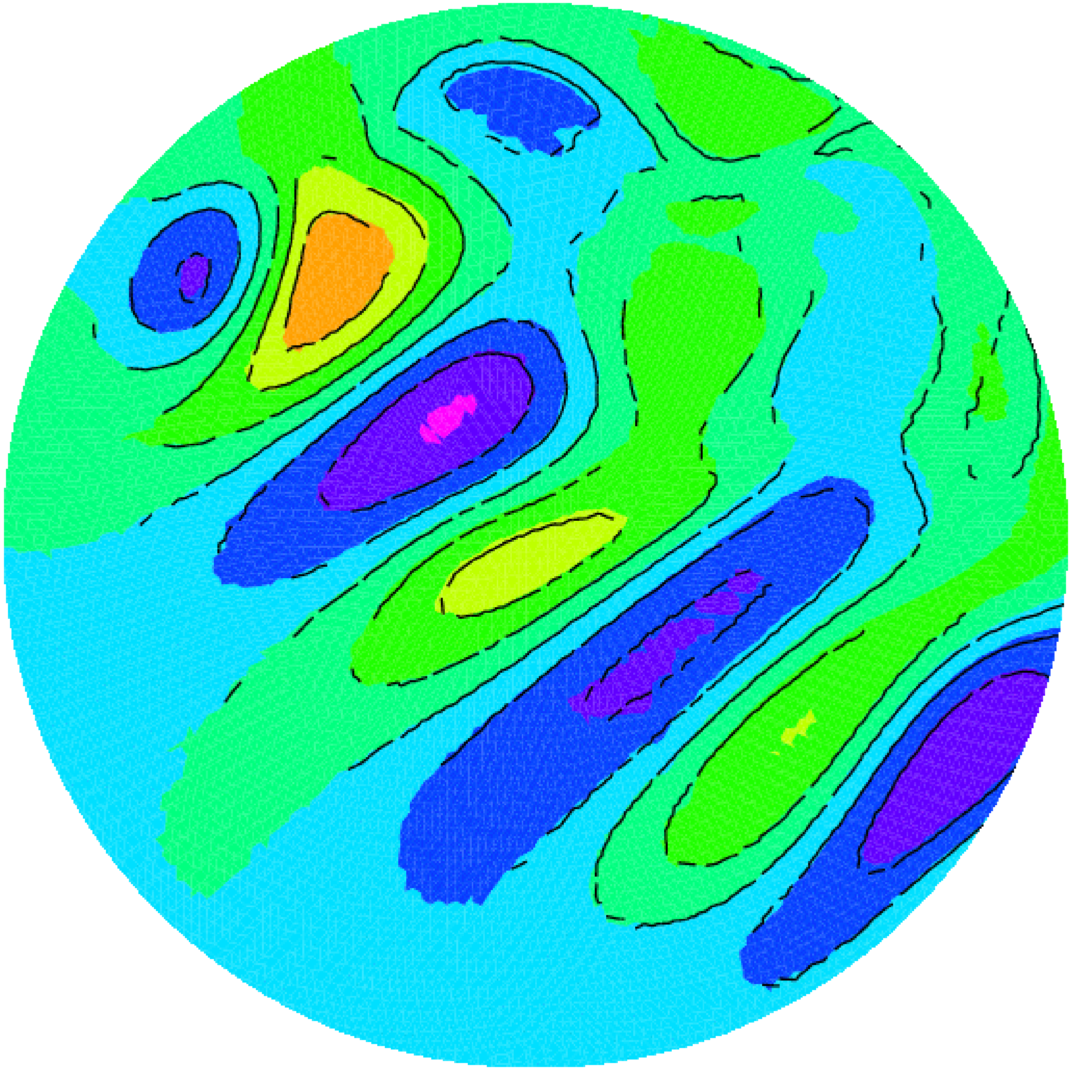
Rossby Haurwitz wave, day 10



Flow over a mountain, day 10



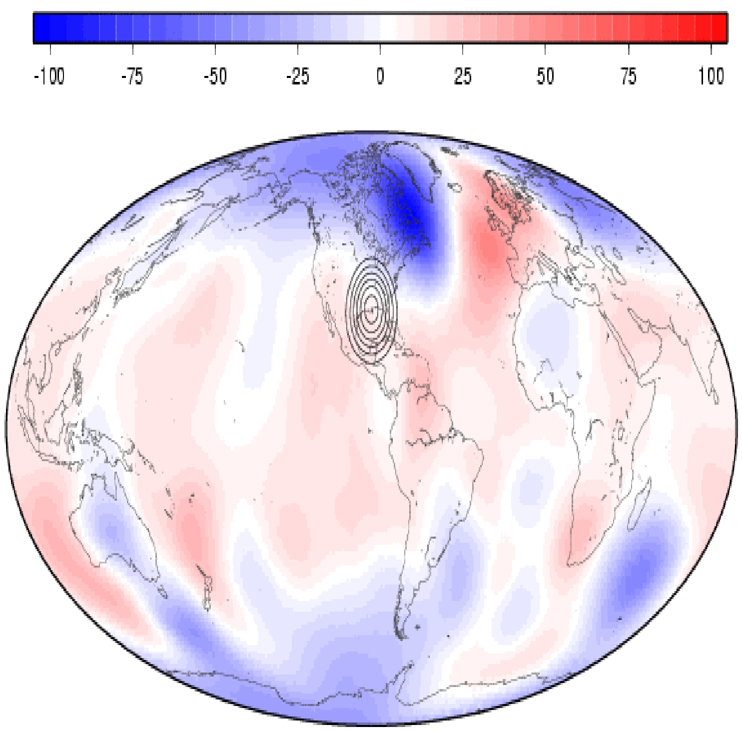
Flow over a mountain: relative vorticity, day 10

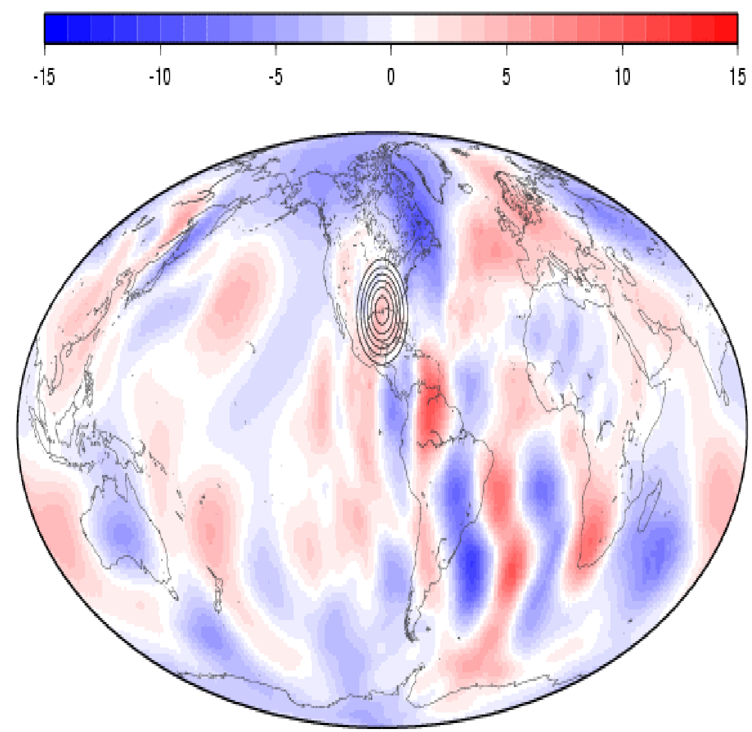


Colour shading:
ICON model results

Black contours:
NCAR reference spectral model

Height field error at day 15

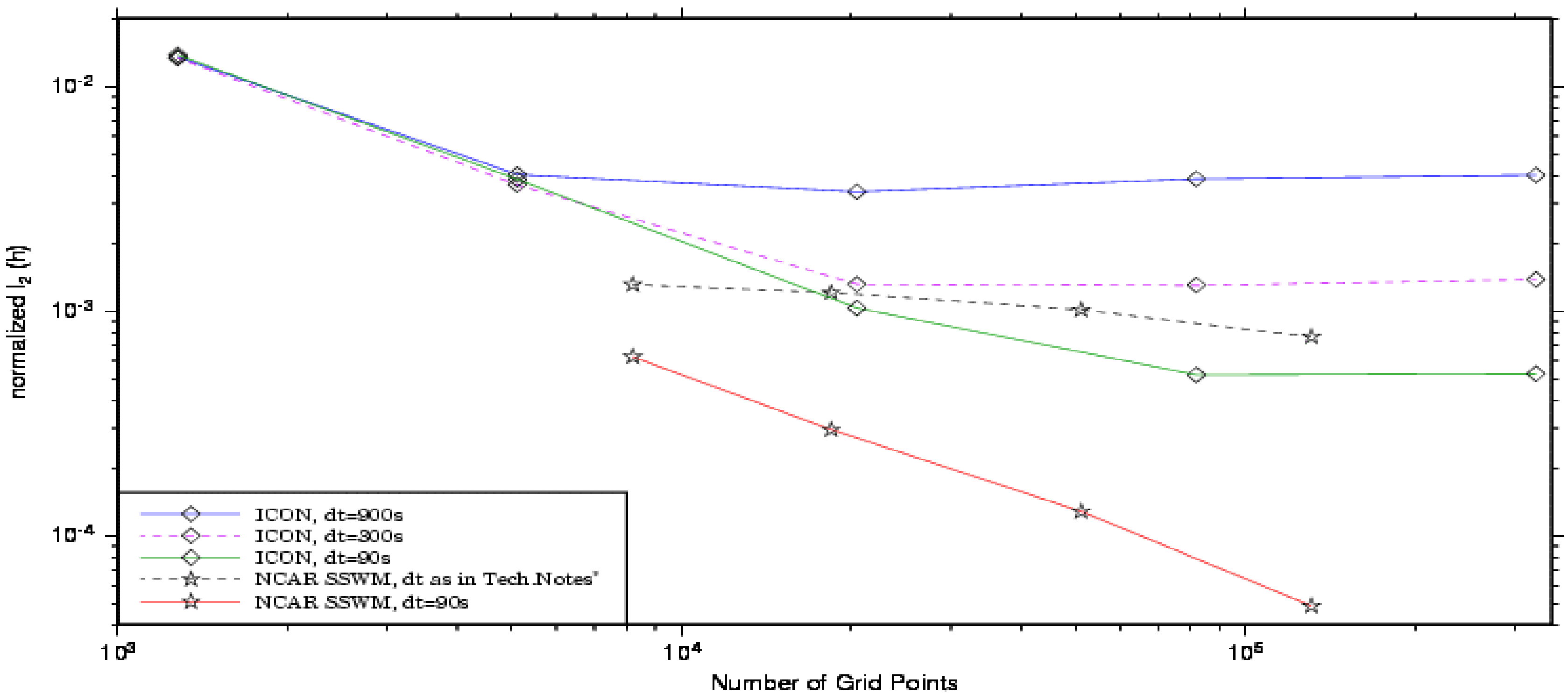




dx≈120 km, dt = 900 s

dx≈60 km, dt = 90 s

Error at day 15, convergence test



TEST CASE 5. L2 NORM AT DAY 15. NCAR SSWM T213/dt=90s as reference*

NCAR SSWM: T42, T63, T106 and T170; ICON: refinement levels 4 to 8, optimized grids;

*black dashed line: reference as in NCAR Tech.Notes: T213/dt=360s

“Shallowness is the greatest vice”

Oscar Wilde

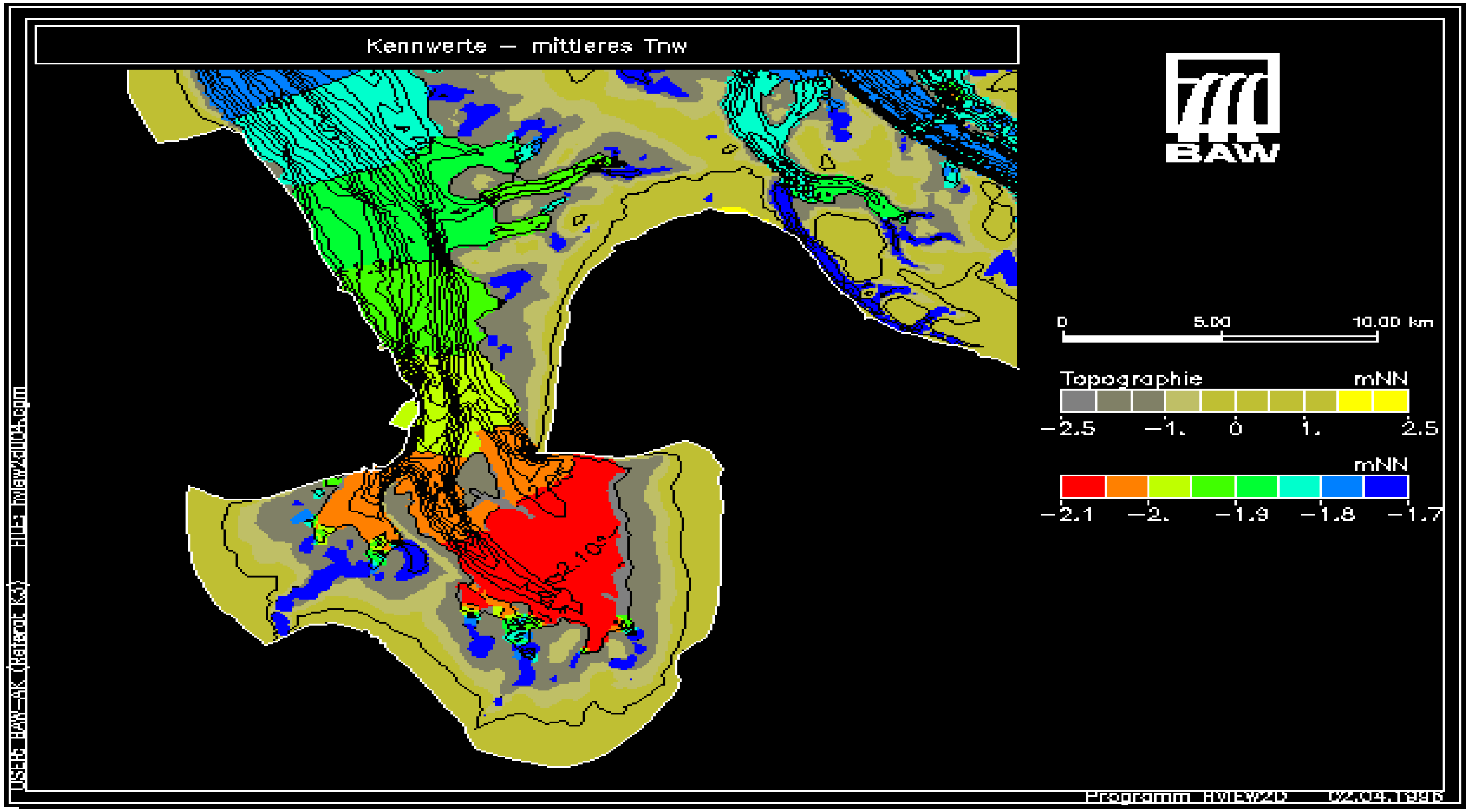
Options for vertical discretization

- **Hybrid pressure vertical coordinate + new horizontal discretization: preliminary 3D hydrostatic ICON model**

- **Terrain following normalized height coordinate + new horizontal discretization: first choice for operational nonhydrostatic model**

- **Non normalized height coordinate: cut cells (B., JCP 2000, Rosatti and B., Proc. ICFD, 2004)**

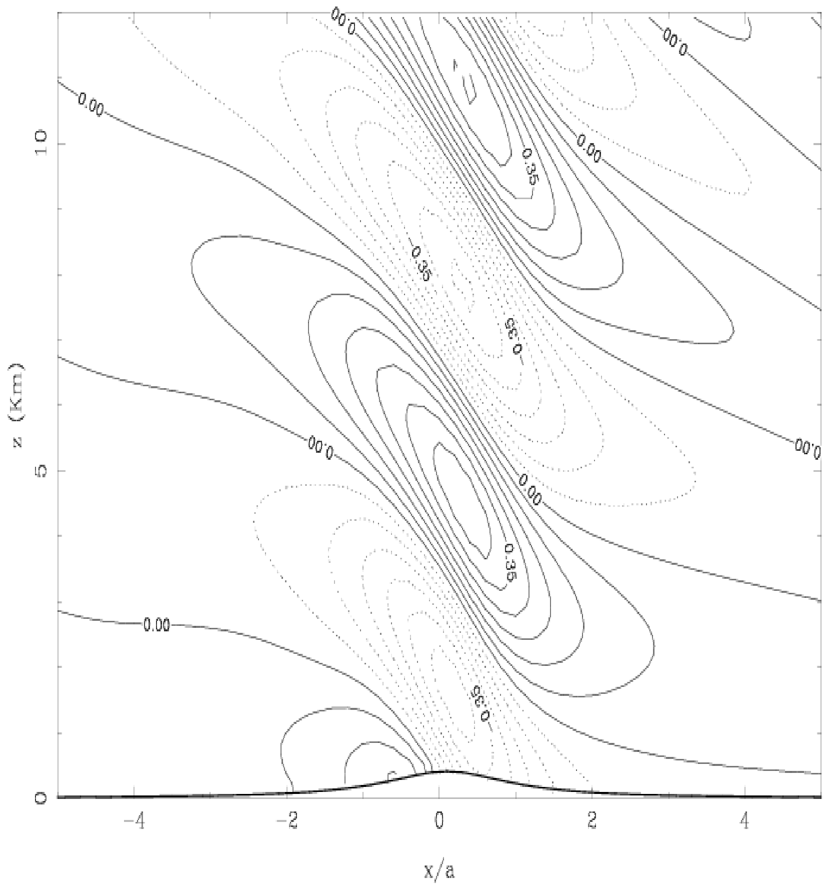
Nonhydrostatic coastal modelling



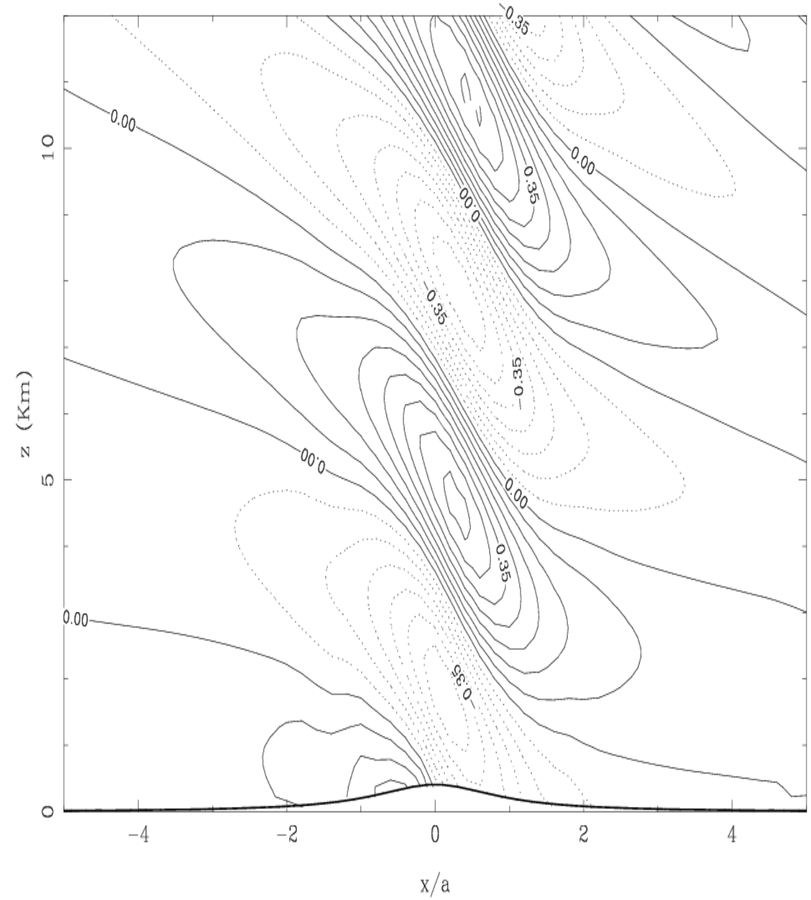
•**Results: G.Lang, Bundesanstalt für Wasserbau, Germany**

•**Numerical model: Casulli and Walters, IJNMF, 2000**

Cut cells + RBF interpolation



Terrain following model (LM)



Cut cell nonhydrostatic dynamical core (ARPA Bologna)

Computational advantages of cut cells

	CPU time for 1 hour	CPU time solver	COMM time solver
SE	88.95 s	45.03 s	11.95 s
SIZ	56.40 s	26.16 s	5.12 s

	Residual 1% of initial value	Residual 0.1% of initial value	Residual 0.01% of initial value
SI	6 iter	21 iter	50 iter
SIZ	8 iter	17 iter	21 iter

Simulations run by D.Cesari (ARPA Bologna)

Future work

- Shallow water model on locally refined grids: optimized data structure and parallelization

- Hydrostatic, 3D model on locally refined grids

- Coupling to existing MPI-M/DWD physics packages, impact of spurious modes on simulations with full physics

- Sensitivity of results to local refinement