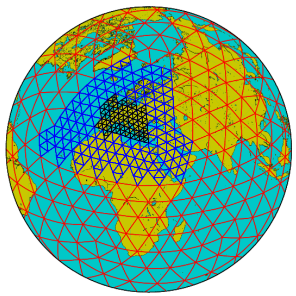


Non-hydrostatic modelling with ICON

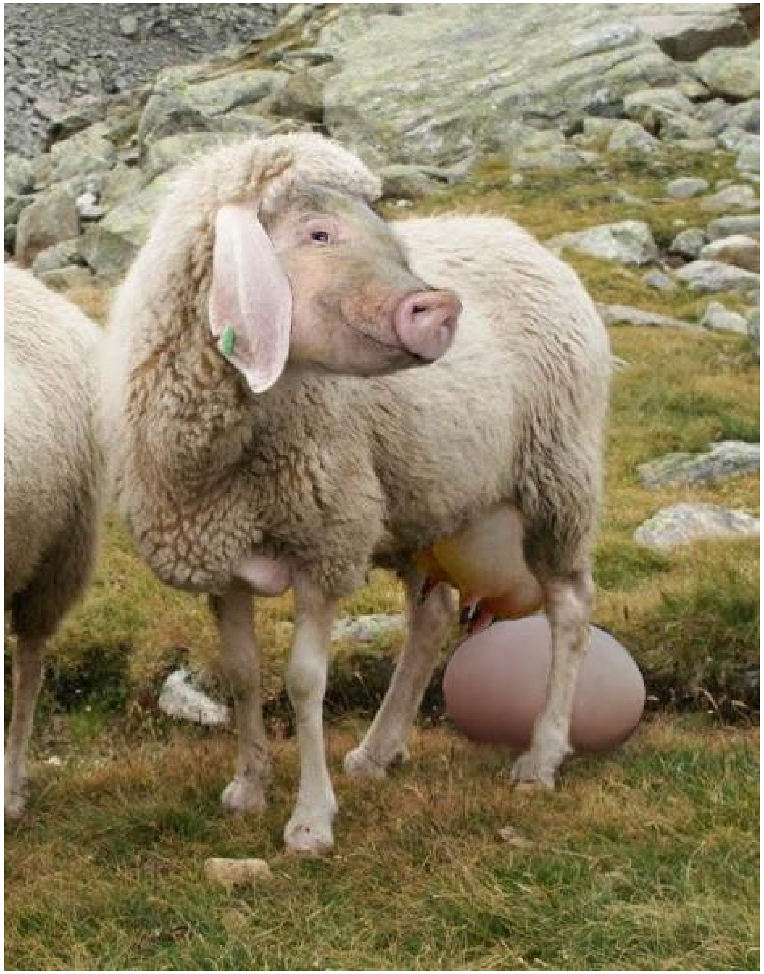
Almut Gassmann

Max Planck Institute for Meteorology
Hamburg, Germany

ICON: tool for NWP and climate applications

Wishes for the project some years ago:

- non-hydrostatic atmospheric model
- dynamics in grid point space
- triangular grid based on the tesselation of an icosahedron
- local zooming with static grid refinement
- transport scheme: conservative, positive definit, efficient
- dynamics conserves mass, energy, potential vorticity
- physics parameterizations from COSMO, ECHAM
- coupling to ocean model, atmospheric chemistry, hydrology, and land model
- common software framework supports different models (ocean, atmosphere; grids)
- modulartity, portability
- scalability and efficiency on multicore architectures



from: http://infoskript.de/uploads/pics/Wollmilchsau.jpg

Overview for patchwork talk

1. Non-hydrostatic equation set
2. C-grid discretisation on triangles and hexagons/pentagons
3. Special topics concering discretisations
   a) SICK (Hollingsworth et al., 1983)
   b) terrain-following coordinates
   c) advection schemes
4. Physics parameterization packages
5. Grid refinement
6. Efficiency, scalability
7. Outlook

Non-hydrostatic atmospheric model - model core formulation

prognostic equations

$$\frac{\partial \vec{v}}{\partial t} = -\frac{\vec{\omega}_a}{\varrho} \times \varrho\vec{v} - \nabla(K+\Phi) - c_{pd}\theta_v \nabla \Pi$$

$$\frac{\partial \varrho}{\partial t} = -\nabla \cdot (\varrho \vec{v})$$

$$\frac{\partial \Pi}{\partial t} = -\frac{R_d \Pi}{c_{vd}\varrho\theta_v} \nabla \cdot (\theta_v(\varrho\vec{v}))$$

$$\frac{\partial \varrho\theta_v}{\partial t} = -\nabla \cdot (\theta_v(\varrho\vec{v}))$$

+physics

$|\cdot\rho\mathbf{v}$ (to obtain energy equ.)

Π = Exner pressure
θ_v = virtual pot. temperature
ρ = density
v = 3D velocity vector
K = spec. kinetic energy
Φ = geopotential
ω_a = 3D abs. vorticity vector
R_d = gas constant for dry air
c_{vd} = spec. heat capacity at constant volume for dry air
c_{pd} = spec. heat capacity at constant pressure for dry air

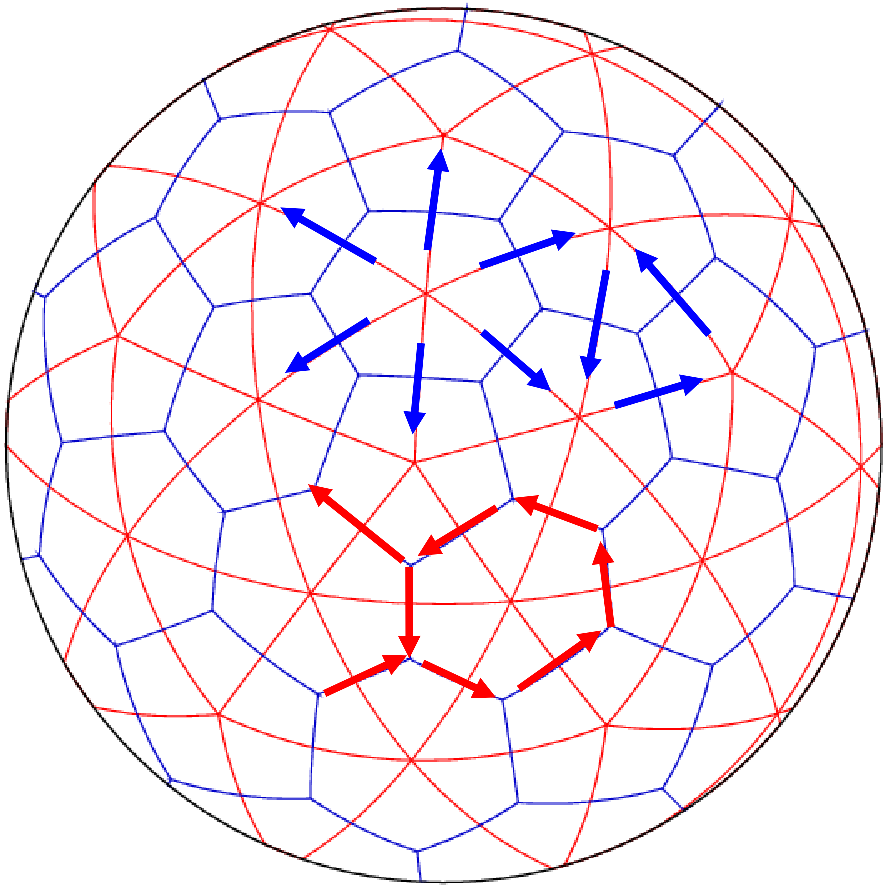
\+ Transport equations for specific moisture quantities.

Hamiltonian description
- discretisation of Poisson backets
- symplectic time integration

$$\frac{\partial \mathcal{F}}{\partial t} = \{\mathcal{F}, \mathcal{H}\}$$

Triangular and hexagonal C-grids

$$\mathbf{j_1} = \mathbf{j}$$
$$\mathbf{j_2} = -\frac{1}{2}\mathbf{j} - \frac{\sqrt{3}}{2}\mathbf{i}$$
$$\mathbf{j_3} = -\frac{1}{2}\mathbf{j} + \frac{\sqrt{3}}{2}\mathbf{i}$$
$$v_1 + v_2 + v_3 = 0$$

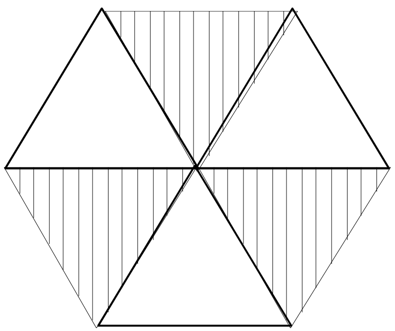


$$\mathbf{i_1} = \mathbf{i}$$
$$\mathbf{i_2} = -\frac{1}{2}\mathbf{i} + \frac{\sqrt{3}}{2}\mathbf{j}$$
$$\mathbf{i_3} = -\frac{1}{2}\mathbf{i} - \frac{\sqrt{3}}{2}\mathbf{j}$$
$$u_1 + u_2 + u_3 = 0$$

$$\mathbf{v} = u\mathbf{i} + v\mathbf{j} = \frac{2}{3}\left(u_1\mathbf{i_1} + u_2\mathbf{i_2} + u_3\mathbf{i_3}\right) = \frac{2}{3}\left(v_1\mathbf{j_1} + v_2\mathbf{j_2} + v_3\mathbf{j_3}\right)$$

$$\frac{\partial \alpha}{\partial x_1} + \frac{\partial \alpha}{\partial x_2} + \frac{\partial \alpha}{\partial x_3} = 0.$$

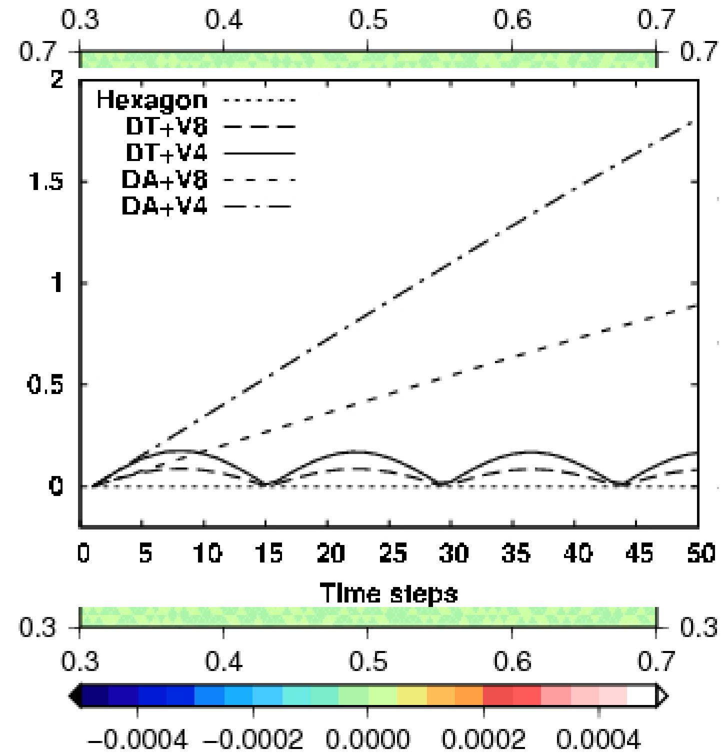
Checkerboard problem
Shallow water model



Fulfillment of the constraint:

No, triangular C-grid

Yes, hexagonal C-grid with a special tangential wind reconstruction.



Triangular C-grid

Divergence field for linear geostrophic adjustment problem with poorly resolved Rossby deformation radius.

$$\tilde{v}_1^1 + \tilde{v}_2^2 + \tilde{v}_3^3 = 0. \quad D^t_{l,u} = \pm \frac{4}{3d}(v_1 + v_2 + v_3), \qquad \sum_{u \in h} D^t_u = \sum_{l \in h} D^t_l.$$

$$\tilde{u}_1^1 + \tilde{u}_2^2 + \tilde{u}_3^3 = 0 \quad \zeta^t_{l,u} = \mp \frac{4}{3d}(u_1 + u_2 + u_3). \qquad \sum_{u \in h} \zeta^t_u = \sum_{l \in h} \zeta^t_l,$$

$$\frac{\partial \alpha}{\partial x_1} + \frac{\partial \alpha}{\partial x_2} + \frac{\partial \alpha}{\partial x_3} = 0.$$

Hexagonal C-grid

Quart. J. R. Met. Soc. (1983), **109**, pp. 417–428

Hydrostatic dycore

An internal symmetric computational instability

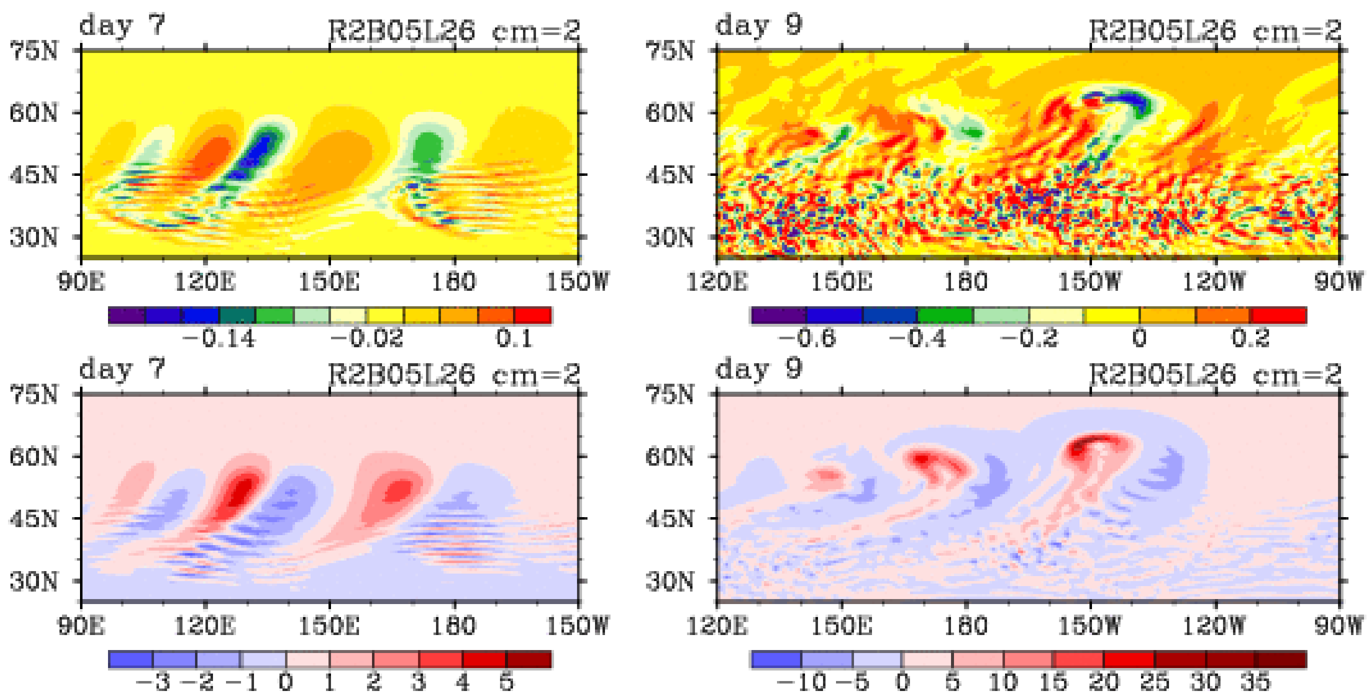
A. HOLLINGSWORTH[1], P. KÅLLBERG[1], V. RENNER[2] and D. M. BURRIDGE[1]
[1] *European Centre for Medium Range Weather Forecasts, Reading.* [2] *Deutscher Wetterdienst, Offenbach am Main, Federal Republic of Germany.*

$$-\mathbf{v}\cdot\nabla\mathbf{v} = -\mathbf{k}\eta_z \times \varrho\mathbf{v} - \nabla K$$

Omega (Pa/s) 850hPa

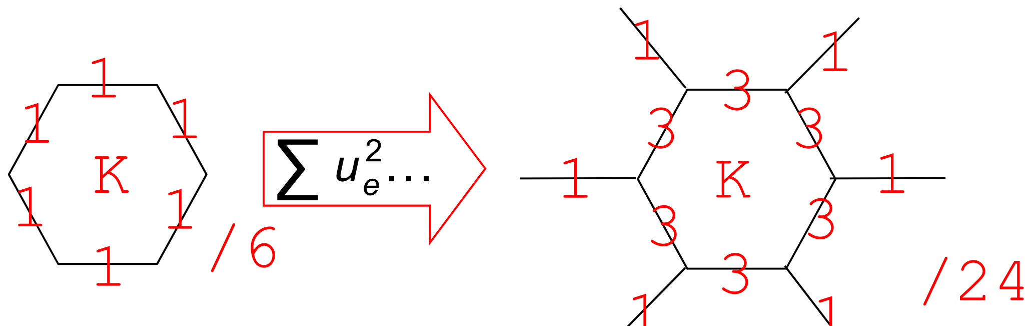
Baroclinic wave test

Vorticity (1/s) 850hPa

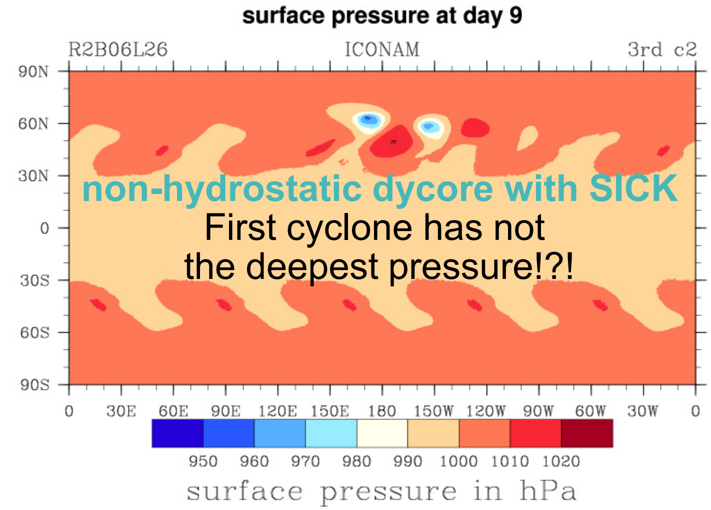


spatial resolution ~ 120km, hexagonal C-grid model (triangular C-grid model has similar problems)

Correction for SICK



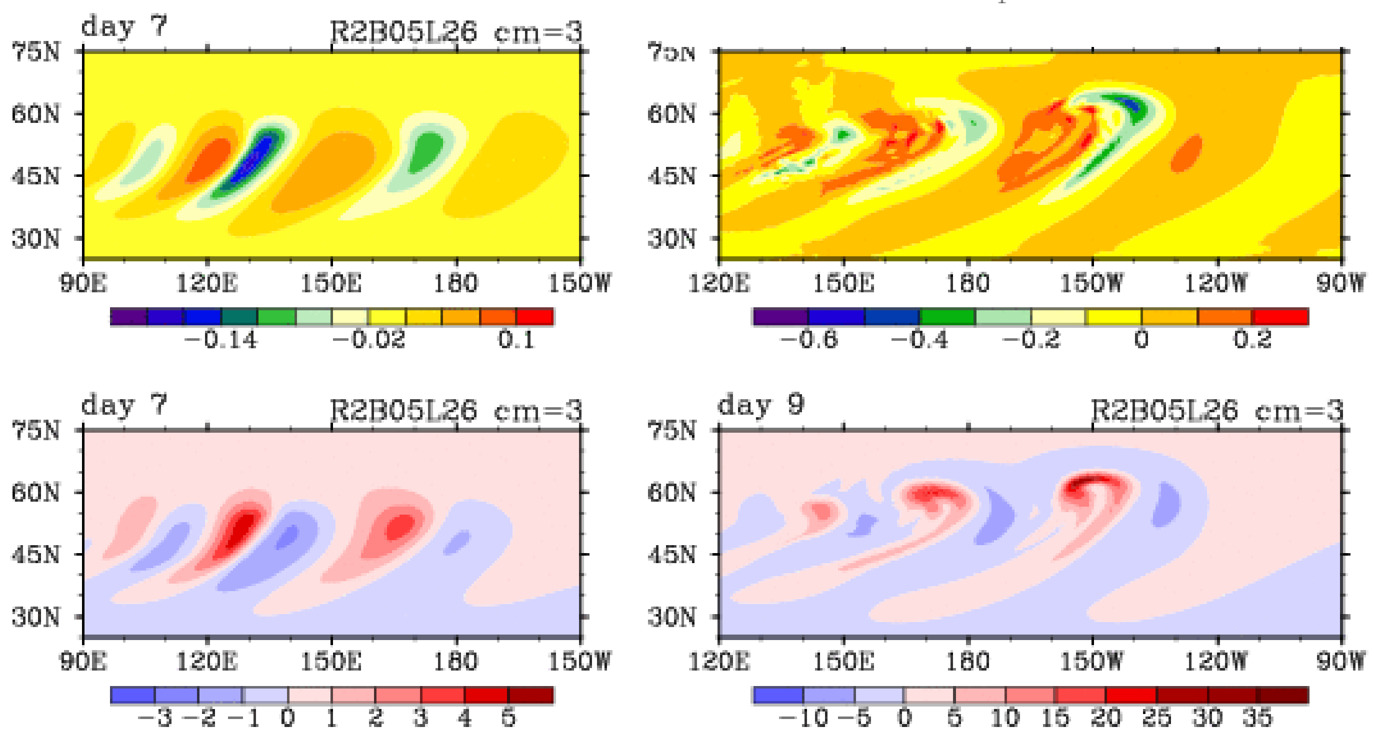
K: spec. kinetic energy



Omega (Pa/s)
850hPa

Baroclinic wave test (hydrostatic dycore)

Vorticity (1/s)
850hPa



spatial resolution ~ 120km, hexagonal C-grid model (triangular C-grid model has similar solution)

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für Meteorologie

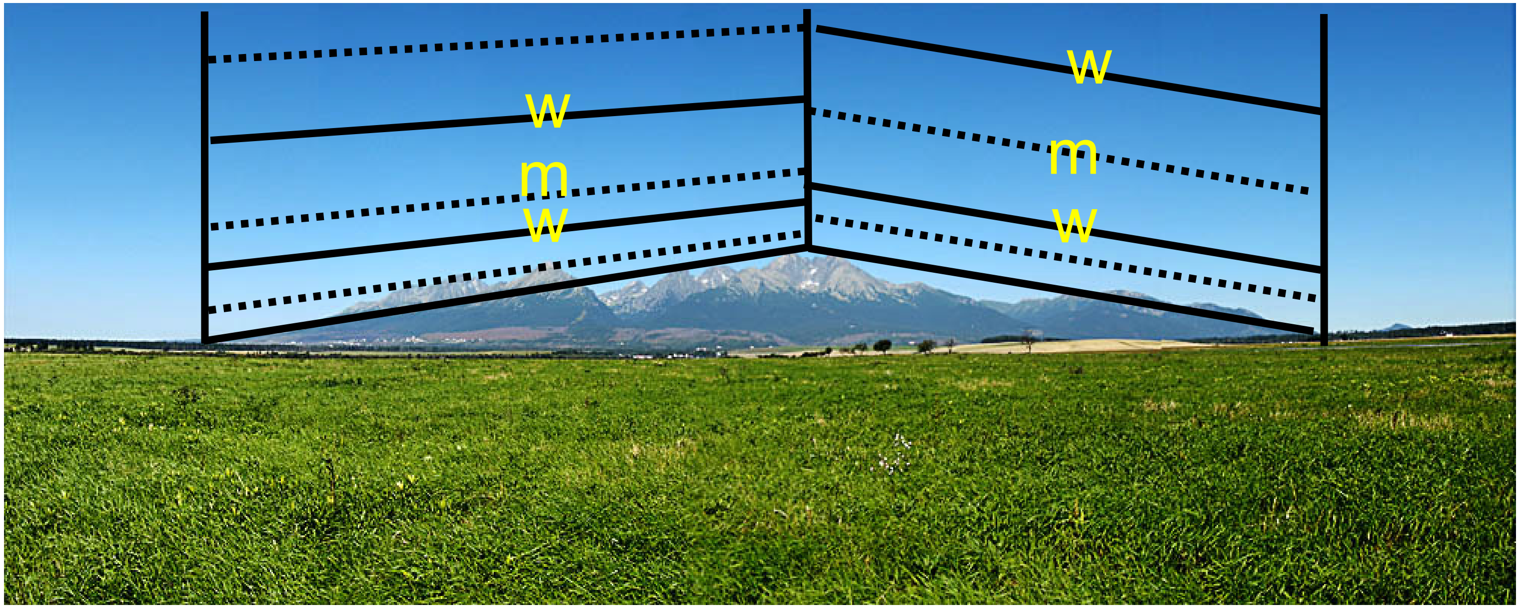
Almut Gassmann (MPI-M), Günther Zängl (DWD)

Non-hydrostatic dycore
L-grid staggering + terrain-following coordinates

- *interface* levels height-centered between *main* levels
- horizontal pressure gradient:
  - Covariant velocity equations
  - Do not remove background reference profile
  - Care with lower boundary

$$\frac{\partial u_{orth}}{\partial t} = \frac{\partial u_{cov}}{\partial t} - \frac{\partial z}{\partial x}\frac{\partial w}{\partial t}$$

- *main* levels height-centered between *interface* levels
- horizontal pressure gradient:
  - search for neighboring point in the same height
  - reconstruct Exner function using a Taylor expansion until the second order



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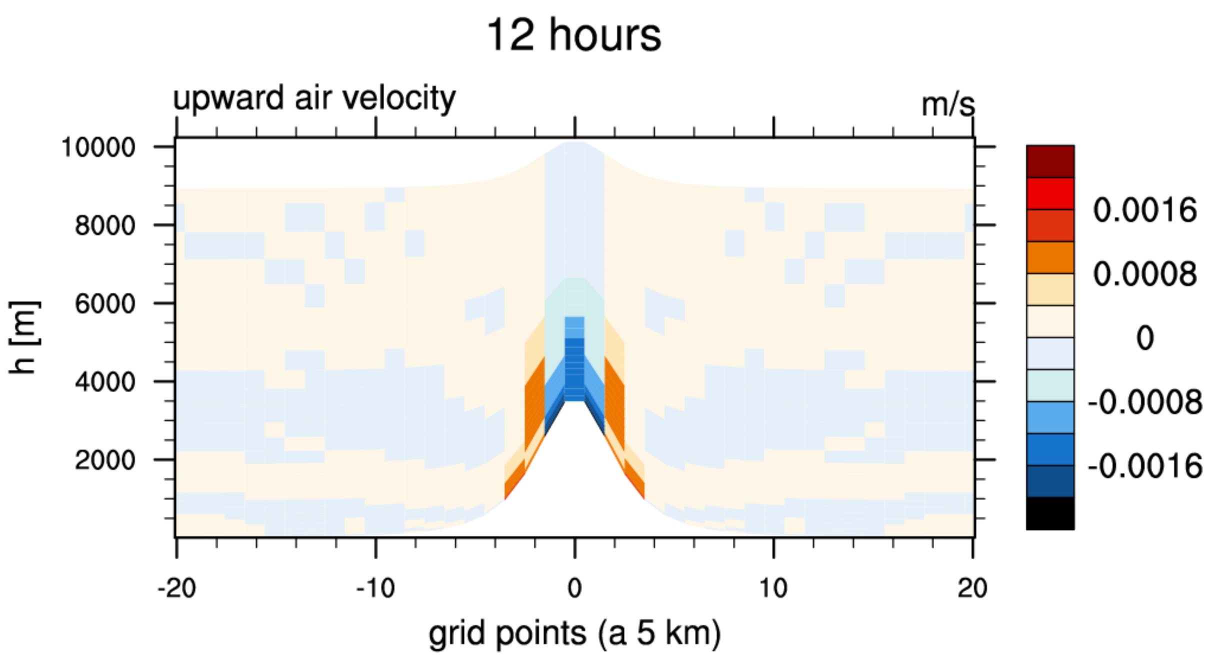
Acid test for terrain-following coordinates: Resting atmosphere over a high mountain

Vertical slice model



Spurious vertical velocities remain in the range of mm/s.

Errors do not spoil higher levels.

$N^2=10^{-4}/s^2$

35 vertical layers, dt=6sec

For *a < 14 km*, the model becomes unstable.
→ SLEVE coordinate
→ Filtering of orography

$$\frac{\partial u_{orth}}{\partial t} = \frac{\partial u_{cov}}{\partial t} - \frac{\partial z}{\partial x}\frac{\partial w}{\partial t}$$

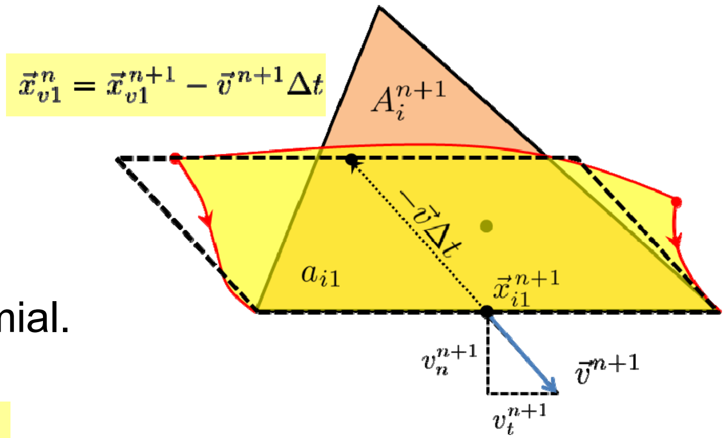
explicit estimate

Bell shaped mountain

$$h = \frac{H_{max}}{\left(1 + \left(\frac{x - x_c}{a}\right)^2\right)^{3/2}}$$

H_{max} = 4 km
a = 14 km

Tracer advection scheme according to Miura (2007)



Departure region a_{ie}:

approximated by **rhomboidally shaped** area.
Assumption: v=const along a given edge

Reconstruction of $q^n(x,y)$:

SGS tracer distribution approximated by 2D polynomial.
Example: linear polynomial (in ICON up to 3rd order)

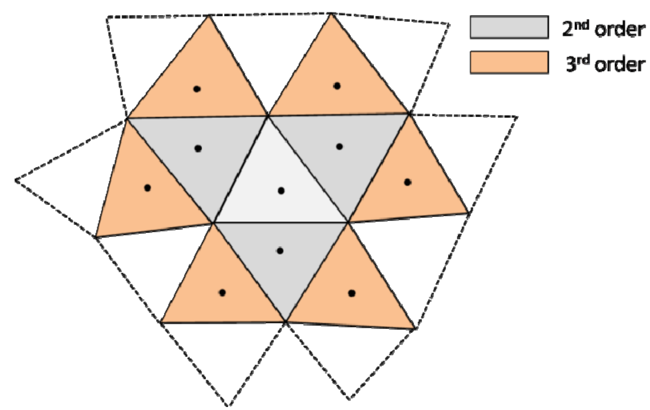
$$q^R(\vec{x}-\vec{x}_i) = q|_{\vec{x}_i}^{n} + \left.\frac{\partial q}{\partial x}\right|_{\vec{x}_i}^{n}(x-x_i) + \left.\frac{\partial q}{\partial y}\right|_{\vec{x}_i}^{n}(y-y_i)$$

(x_i, y_i) : mass point of control volume i

unknown

conservative weighted least squares reconstruction

$$\frac{1}{A_i}\iint_{A_i} q^R(\vec{x}-\vec{x}_i)\,\mathrm{d}A = \overline{q}_i^n$$



Integration:

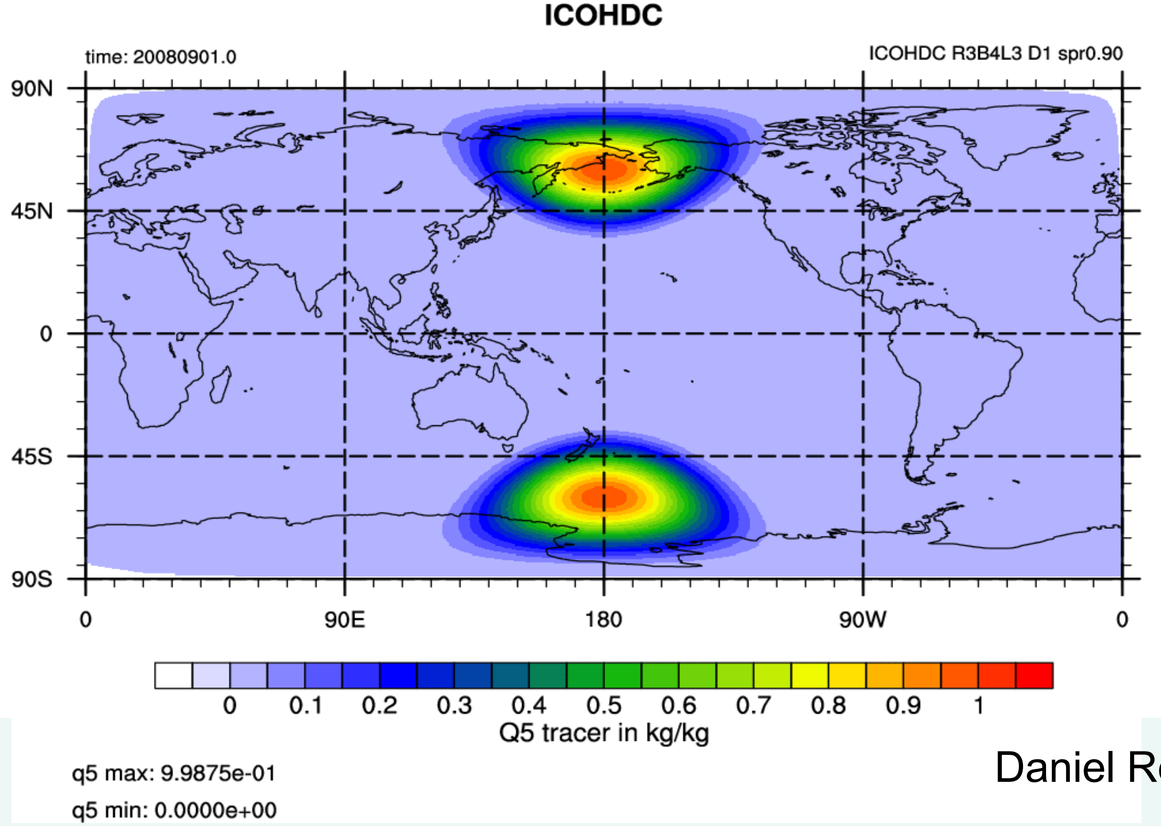
Gauss-Legendre quadrature

Deformational flow test case

- based on **Nair, D. and P. H. Lauritzen (2010):** *A class of Deformational Flow Test-Cases for the Advection Problems on the Sphere*, JCP
- Time-varying, analytical flow field $\vec{V}(\lambda, \phi, t) = \vec{v}(\lambda, \phi)\Psi(t)$
- Tracer undergoes severe deformation during the simulation
- Flow reverses its course at half time and the tracer field returns to the initial position and shape $\Psi(t) = \cos(\pi t/T)$
- Test suite consists of 4 cases of initial conditions, three for non-divergent and one for divergent flows.

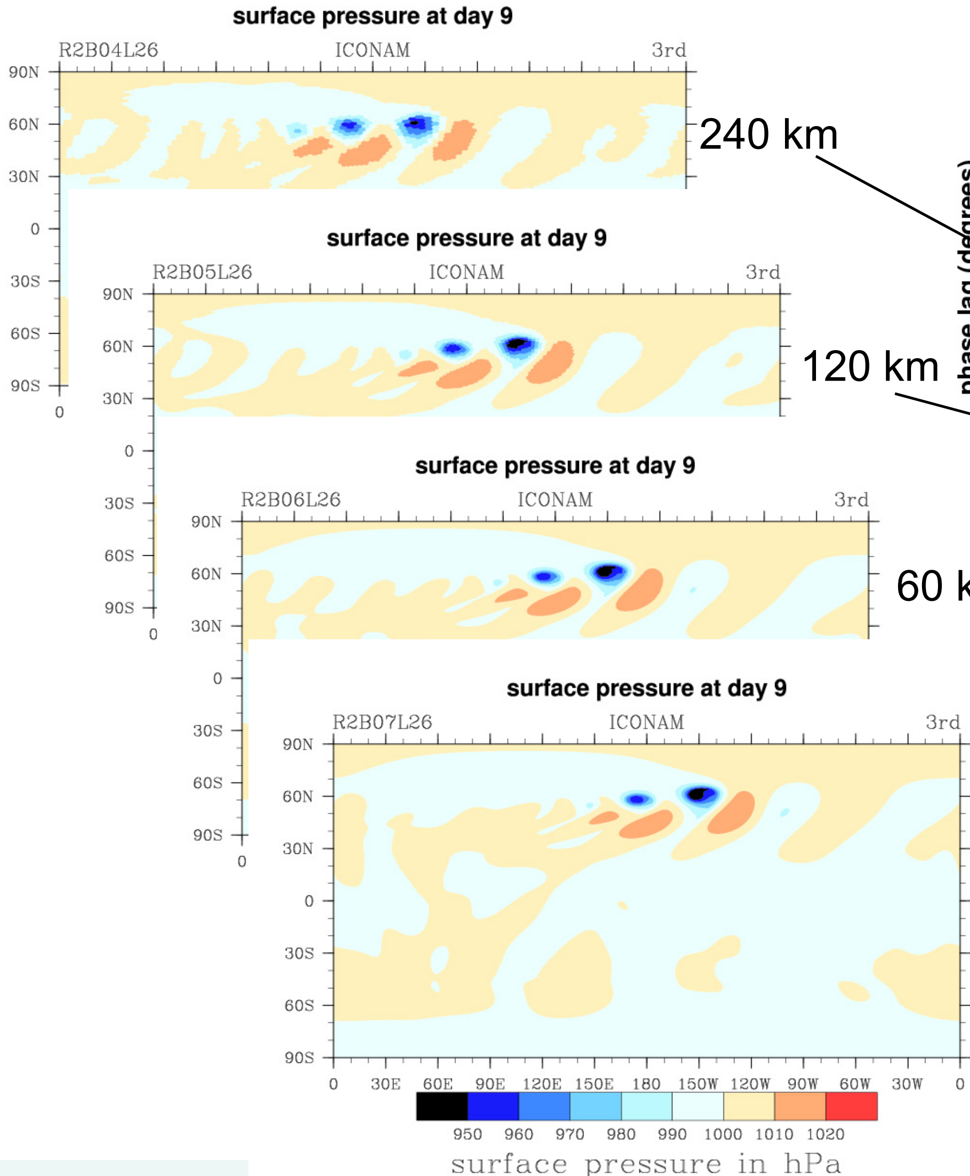
Example:
Tracer field for case 1

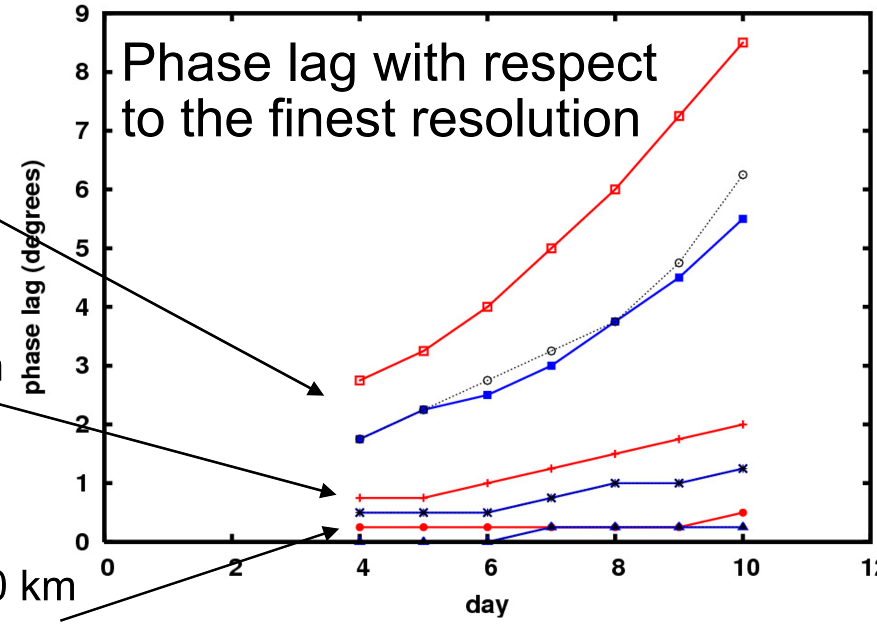
- R3B4 (≈ 95km)
- CFL≈0.5
- flux limiter



Daniel Reinert (DWD)

Temperature advection and baroclinic wave





Non-hydrostatic hexagonal C-grid model runs without diffusion and different orders of θ-advection:

- 2nd order
- 3rd order
- 4th order

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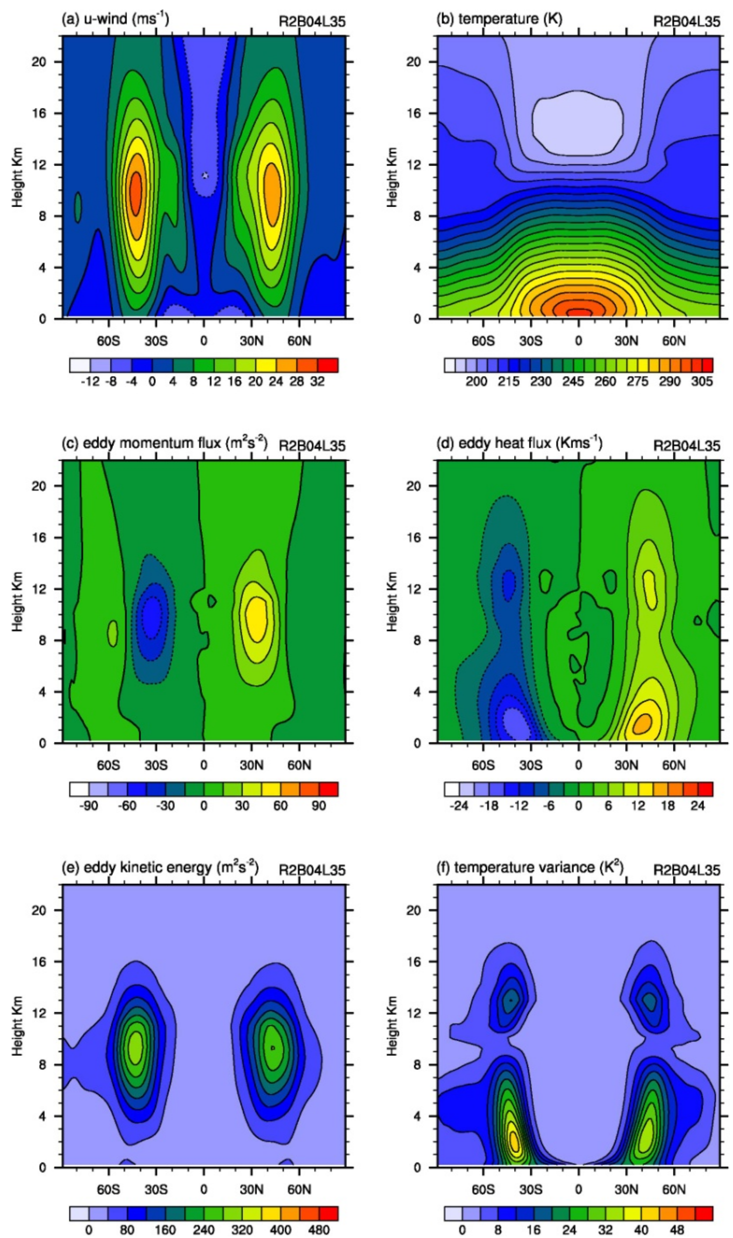
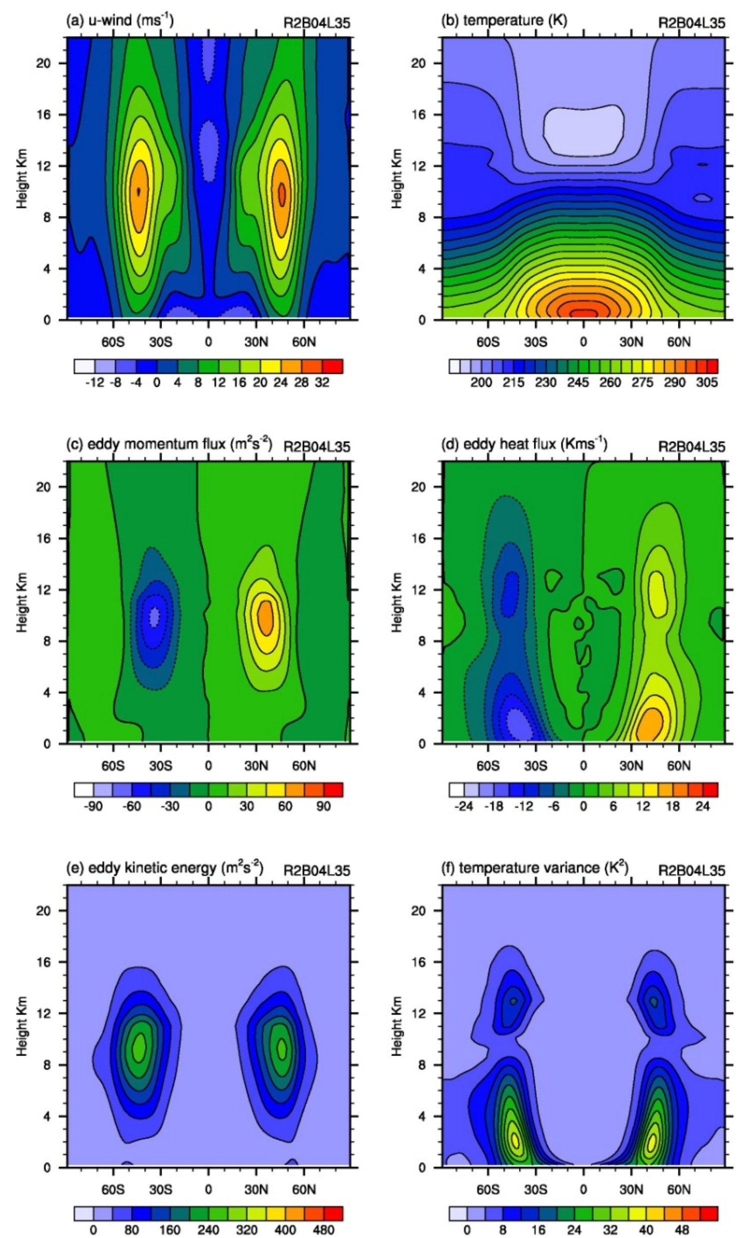
collaboration with Bill Skamarock (NCAR)

Held Suarez test

Triangular C-grid



Hexagonal C-grid



mean climate of the last 100 days in a run of 300 days for R2B04

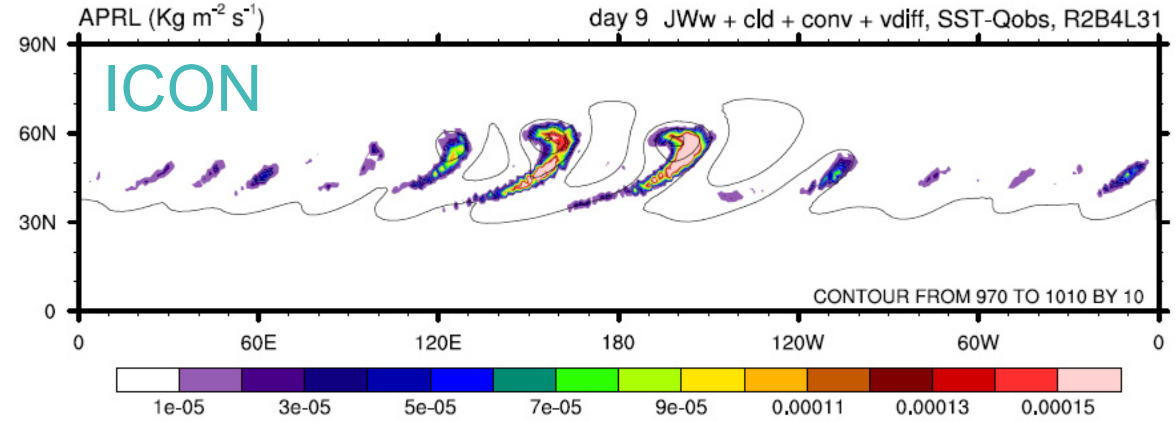
Hydrostatic dycore + physics parameterizations

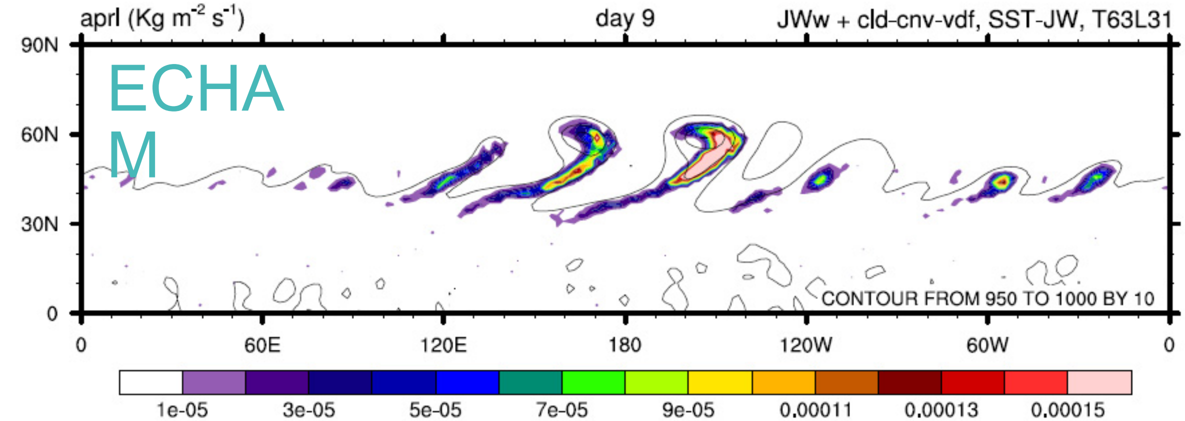
Currently available packages from ECHAM physics
•large scale condensation
•cumulus convection
•turbulence (vertical mixing)
•radiation (not used in this exp.)

For **aqua-planet simulations** we need additionally features for radiation:
- the diurnal cycle
- ozone climatology

<u>Tracer transport in both models:</u>
ECHAM: Lin and Rood (1996) flux-form semi-Lagrangian algorithm (finite volume) with piecewise parabolic reconstruction
ICON
-- Miura scheme with linear reconstruction (that means second order)
-- Limiter in the vertical: semi-monotonous slope limiter
-- Limiter in the horizontal: monotonous flux limiter

Large scale precipitation [6 hours]



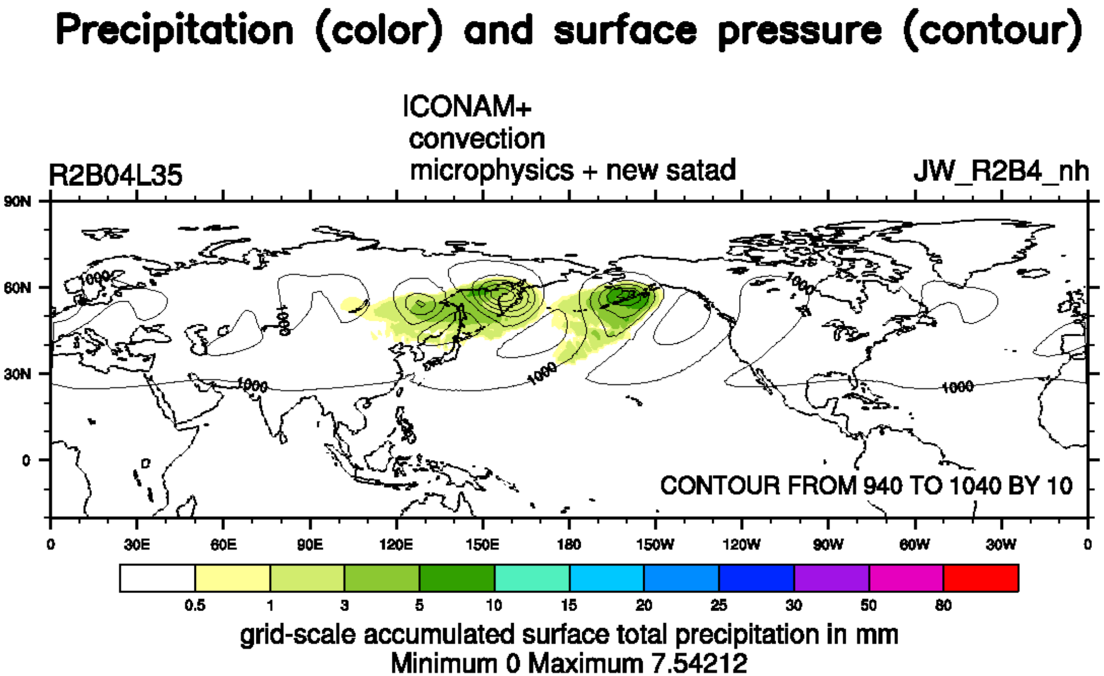


Non-hydrostatic dycore + physics parameterizations

Physics	Author(s)	Current status
Prognostic Microphysics Including prognostic rain and snow	Doms et al. (2004), Seifert and Crewell (2008)	Tested
Saturation adjustment assumption of constant density	Blahak, Seifert	Tested
Convection	Tiedtke-Bechtold	Tested
RRTM-Radiation	Taken from ECHAM	Tested
Cloud cover	Köhler	Technical and physical testing
Turbulent transfer and diffusion Including prognostic TKE	Raschendorfer	Under implementation

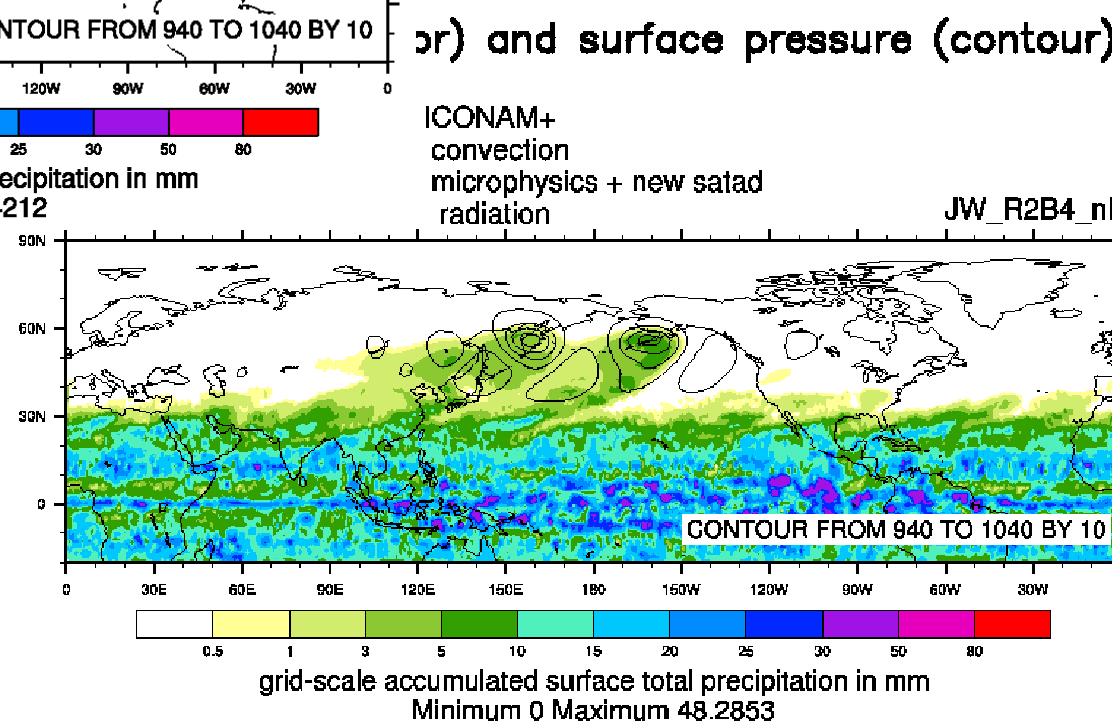
Kristina Fröhlich, Thorsten Reinhardt, Martin Köhler (DWD)

Non-hydrostatic dycore + physics parameterizations



Baroclinic wave experiment without turbulence parameterization

← without radiation



with radiation →

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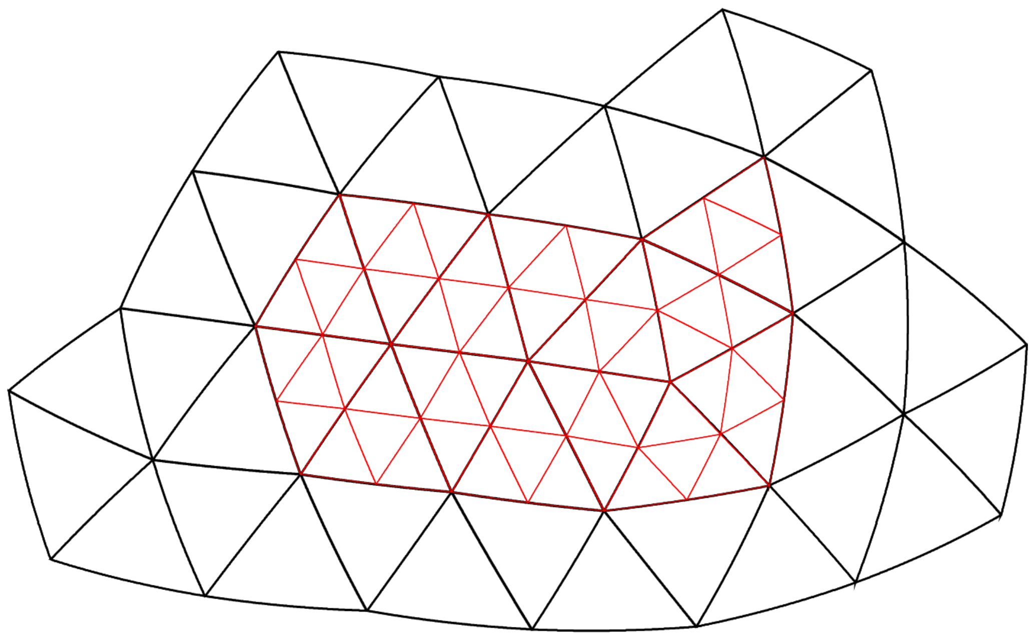
Grid refinement

Two-way nesting -- algorithm:

•one time step in parent domain (black)
•interpolation of lateral boundary fields/tendencies
•two time steps in refined domain (red)
•feedback from the fine domain to the parent domain, overwrite the parent values

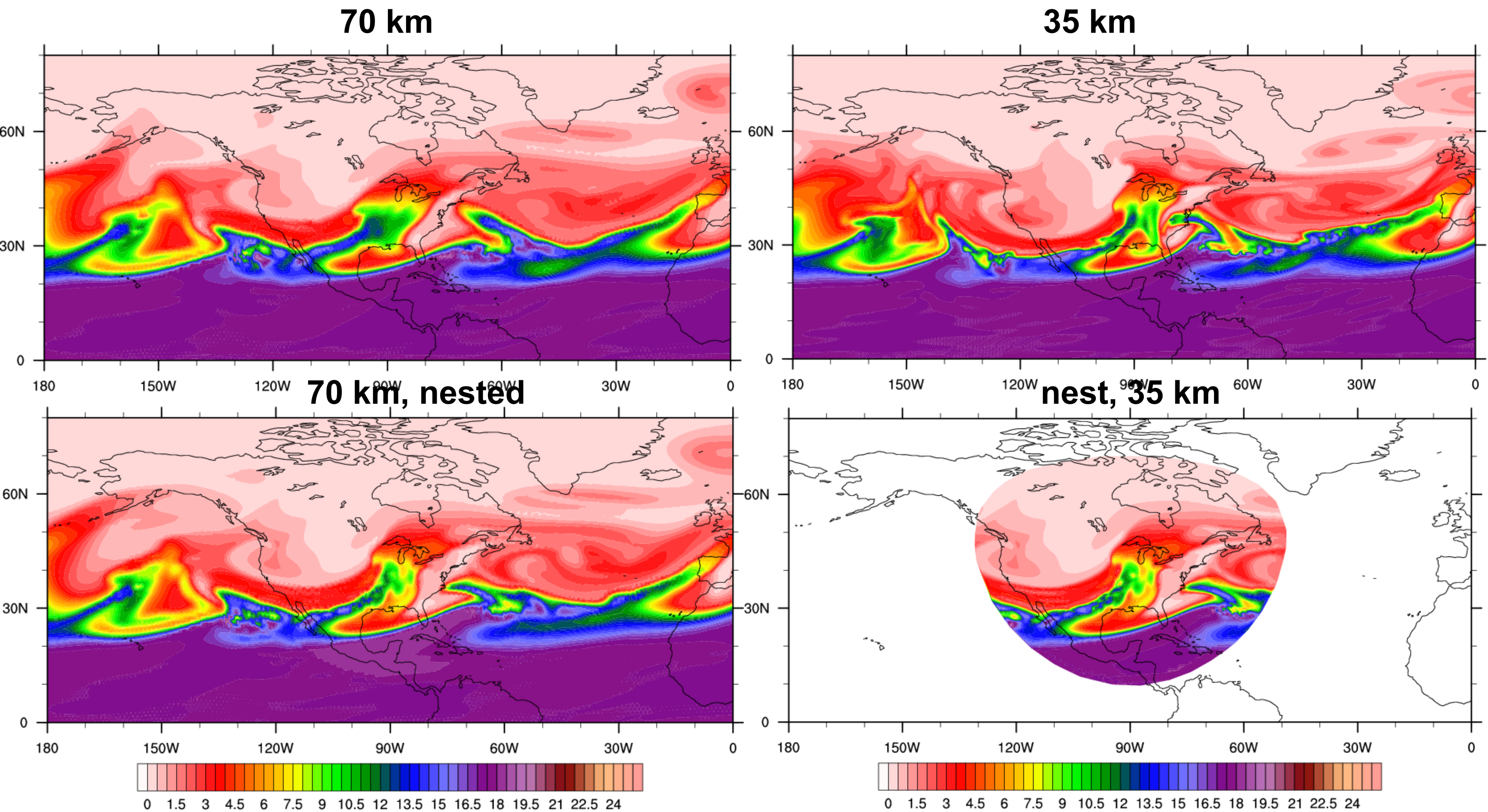


One-way nesting -- algorithm:

•feedback is turned off
•Davies nudging is performed near the nest boundaries

Grid refinement

Baroclinic wave test: QV (g/kg) at 1.8 km AGL on day 14



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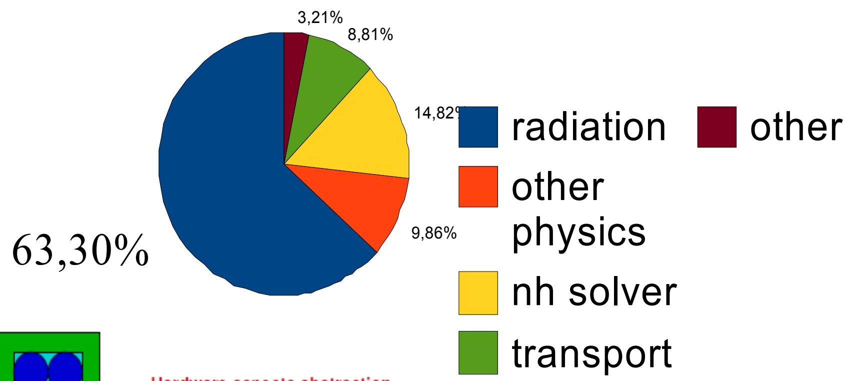
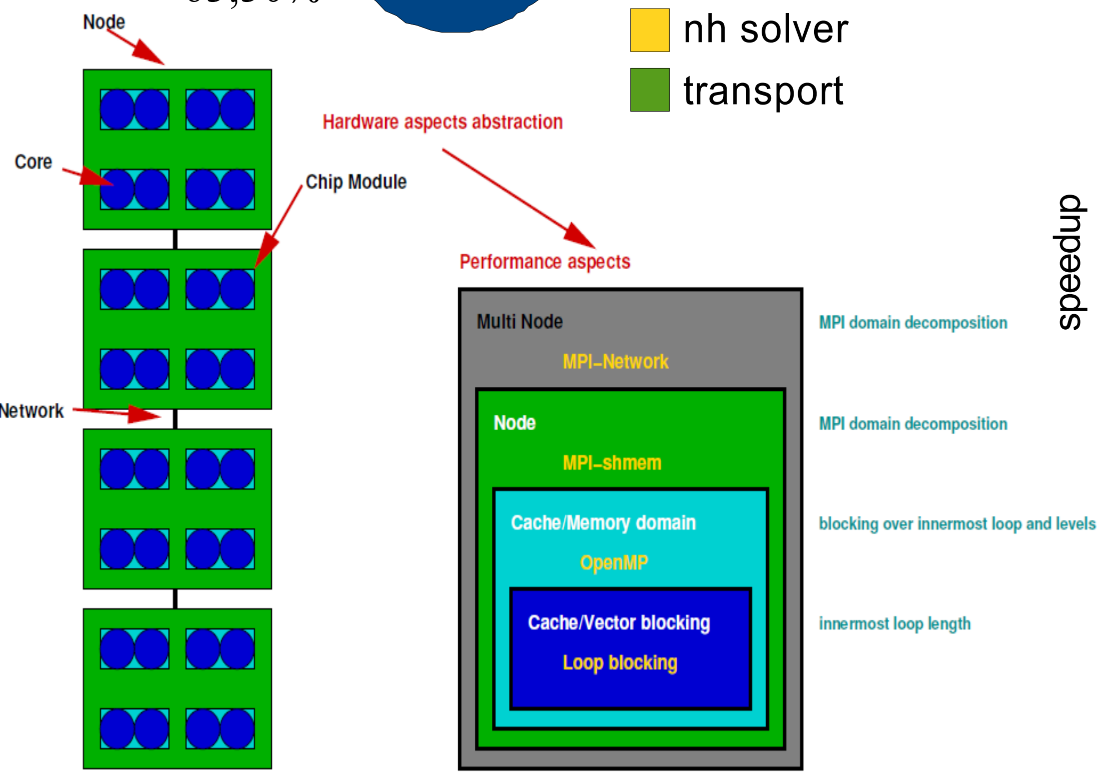
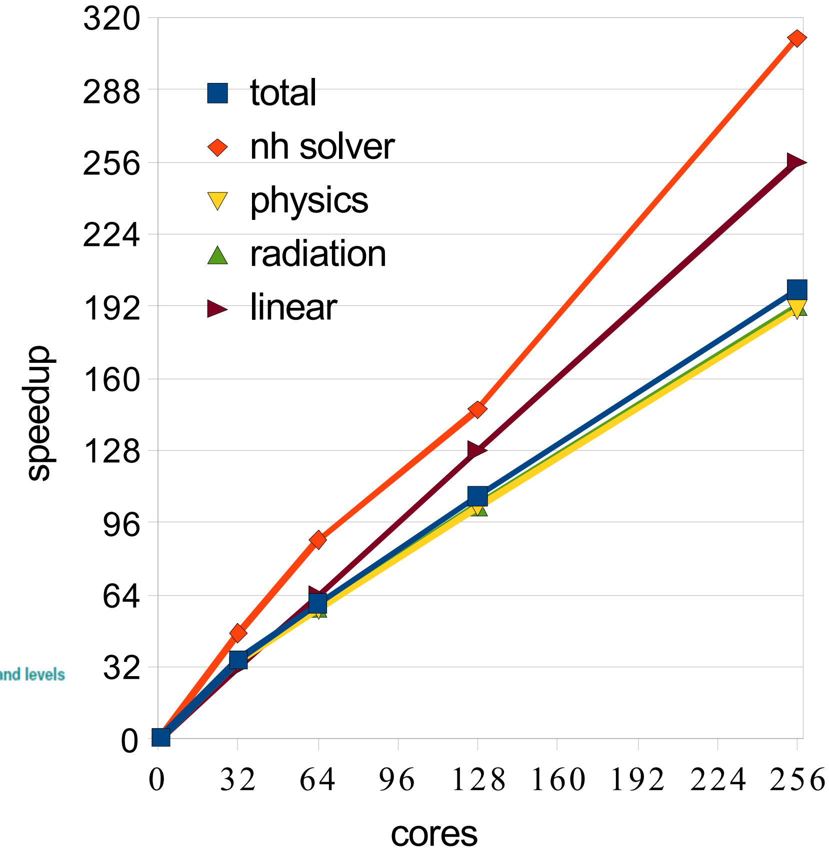
Günther Zängl (DWD)

Efficiency and scalability







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Rainer Johanni (external), Leonidas Linardakis (MPI-M), Günther Zängl (DWD)

Outlook

Further steps for ICON

- consolidation of the code (include remaining physics)
- improvement of efficiency, data structure, IO
- data assimilation + ICON
- preoperational runs next year at DWD
- finalizing ICON grid ocean model at MPI-M
- coupled ocean/atmosphere runs by the end of next year