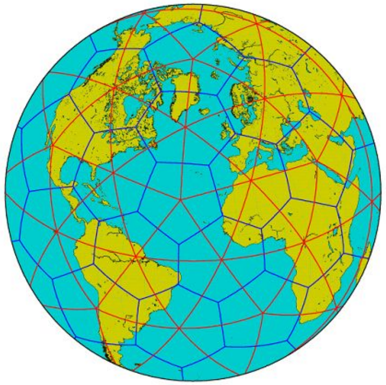
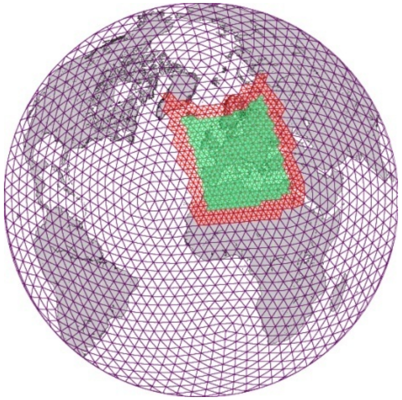
Max-Planck-Institut
für Meteorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand





ICON

The ICOsahedral Nonhydrostatic modelling framework of DWD and MPI-M

Günther Zängl

02.09.2013

Acknowledgements:

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- **Daniel Reinert, Florian Prill (Numerics section, DWD)**
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- **Martin Köhler (Physics parameterizations section, DWD)**
- **Harald Anlauf, Roland Potthast (Data Assimilation section, DWD)**
- **Stefan Körner (HPC section, DWD)**
- **Leonidas Linardakis (Software engineering group, MPI-M)**

- **… and many thanks to all members of the ICON development team for their excellent work!**

Overview

- Introduction: Main goals of the ICON project
- Grid structure, dynamical core and physics parameterizations
- Selected results: from idealized tests to NWP applications
- Computational performance and scaling
- Further planning towards operational use

The ICOsahedral Nonhydrostatic modelling framework

- Joint development project of DWD and Max-Planck-Institute for Meteorology for the next-generation global NWP and climate modeling system
- Nonhydrostatic dynamical core on an icosahedral-triangular C-grid; coupled with full set of physics parameterizations for NWP
- Two-way nesting with capability for multiple nests per nesting level; vertical nesting, one-way nesting mode and limited-area mode are also available
- ECHAM climate physics package currently coupled to hydrostatic dynamical core, transition to nonhydrostatic core in progress
- Hydrostatic ocean model using (basically) the same grid structure is gradually reaching a mature state

Primary development goals

- Better conservation properties (air mass, mass of trace gases and moisture, consistent transport of tracers)
- Grid nesting in order to replace both GME (global forecast model, mesh size 20 km) and COSMO-EU (regional model, mesh size 7 km) in the operational suite of DWD
- Applicability on a wide range of scales in space and time down to mesh sizes that require a nonhydrostatic dynamical core
- Scalability and efficiency on massively parallel computer architectures with O(10^4+) cores
- At MPI-M: Replace ECHAM-MPIOM with ICON for global climate modelling; use limited-area mode of ICON to replace regional climate model REMO.
- Later in this decade: participate in the seasonal prediction project EURO-SIP

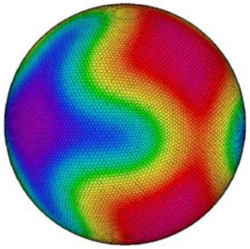
Related projects

ICON-ART (KIT Karlsruhe):

aerosols and reactive trace gases

HD(CP)² (led by MPI-M, Hamburg):

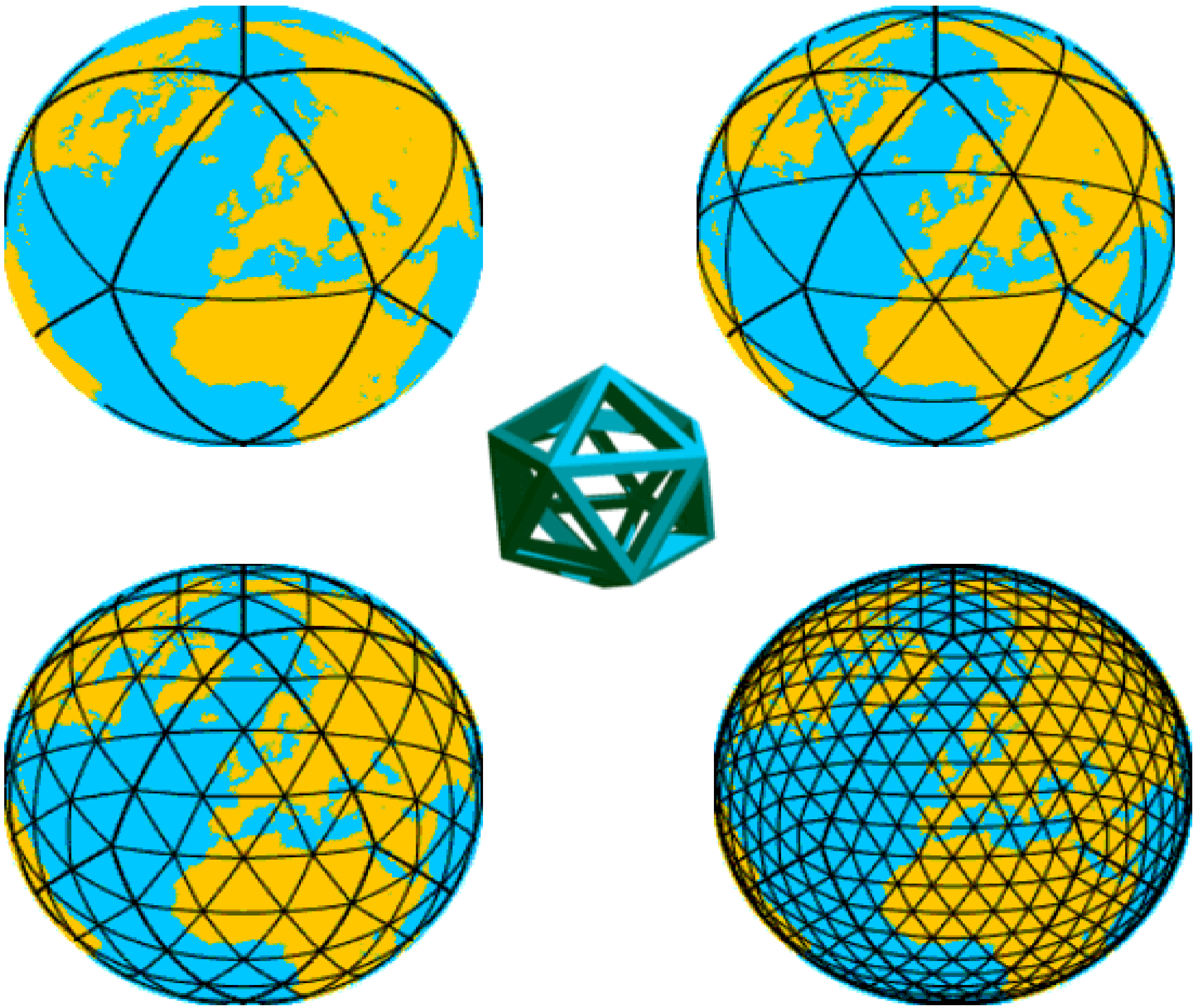
High-definition clouds and precipitation for advancing climate prediction



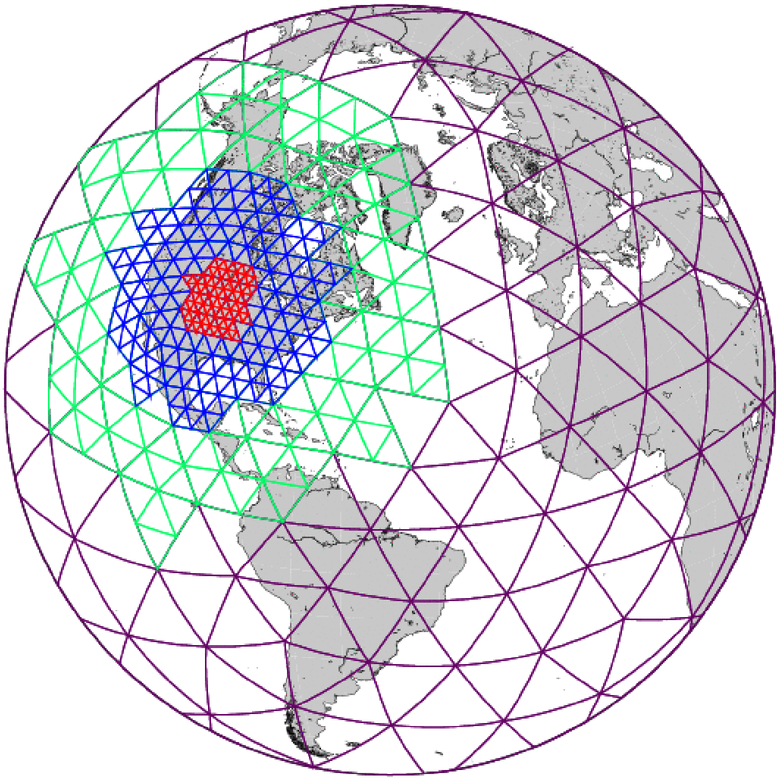
ICOMEX (led by DWD):

ICOsahedral-grid models for Exascale Earth-system simulations

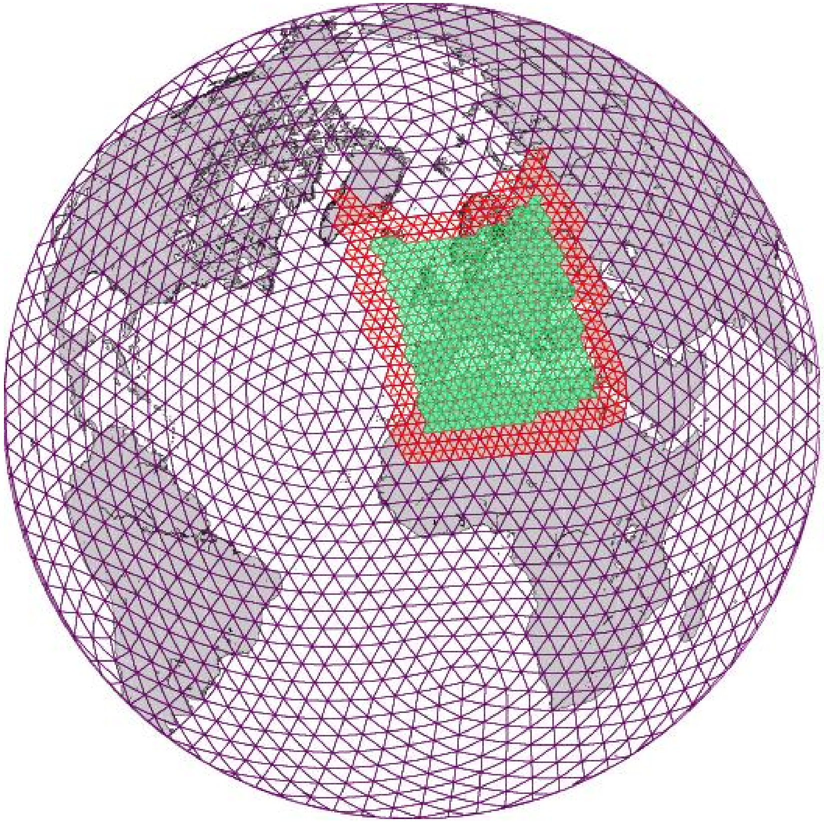
The horizontal grid



Grid structure with nested domains

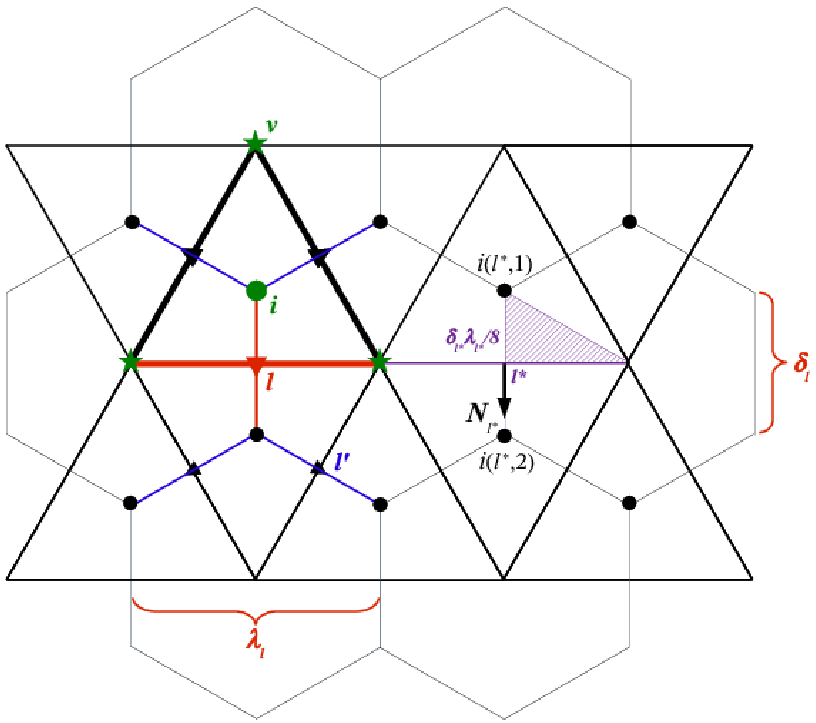


circular nests



latitude-longitude nests

Grid structure …

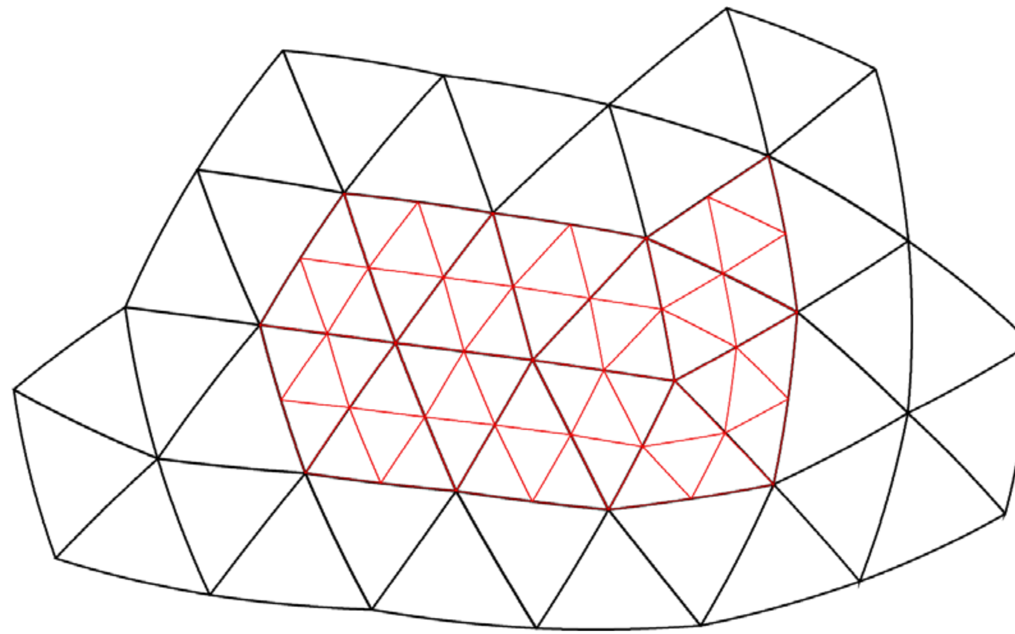


Triangles are used as primal cells

Mass points are in the circumcenter

Velocity is defined at the edge midpoints

… in the presence of nesting



Red cells refer to refined domain

Boundary interpolation is needed from parent to child mass points and velocity points

Nonhydrostatic equation system (dry adiabatic limit)

$$\frac{\partial v_n}{\partial t} + (\zeta + f)v_t + \frac{\partial K}{\partial n} + w\frac{\partial v_n}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial n}$$

$$\frac{\partial w}{\partial t} + \vec{v}_h \cdot \nabla w + w\frac{\partial w}{\partial z} = -c_{pd}\theta_v \frac{\partial \pi}{\partial z} - g$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\vec{v}\rho) = 0$$

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla \cdot (\vec{v}\rho\theta_v) = 0$$

v_n,w: normal/vertical velocity component

ρ: density

θ_v: Virtual potential temperature

K: horizontal kinetic energy

ζ: vertical vorticity component

π: Exner function

blue: independent prognostic variables

Numerical implementation (dynamical core)

- Two-time-level predictor-corrector time stepping scheme; for efficiency reasons, not all terms are evaluated in both sub-steps
- For thermodynamic variables: Miura 2^{nd}-order upwind scheme for horizontal and vertical flux reconstruction; 5-point averaged velocity to achieve (nearly) second-order accuracy for divergence
- implicit treatment of vertically propagating sound waves, but explicit time-integration in the horizontal (at sound wave time step; not split-explicit); larger time step (usually 4x or 5x) for tracer advection / fast physics
- For numerical convenience, the thermodynamic equation is reformulated to an equation for Exner pressure
- Numerical filter: fourth-order divergence damping

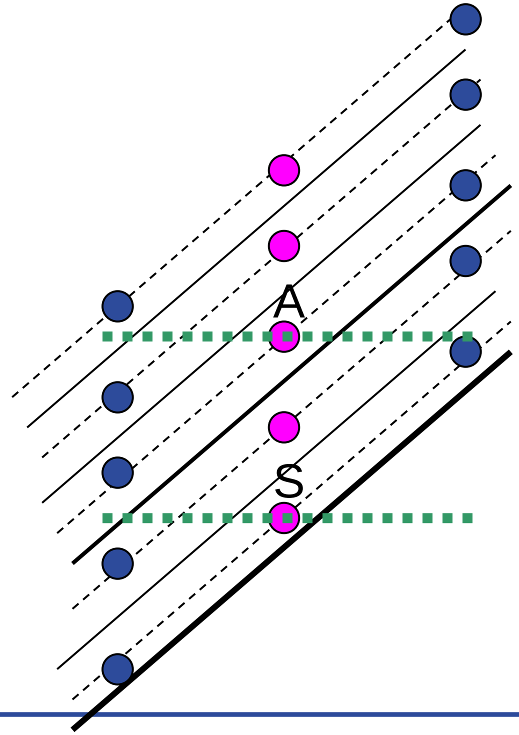
Numerical implementation (tracer advection)

- Finite-volume tracer advection scheme (Miura) with 2nd-order and 3rd-order accuracy for horizontal advection; extension for CFL values slightly larger than 1 available
- 2nd-order MUSCL and 3rd-order PPM for vertical advection with extension to CFL values much larger than 1 (partial-flux method)
- Monotonous and positive-definite flux limiters
- Option to turn off advection of cloud and precipitation variables (and moisture physics) in the stratosphere
- Option for (QV) substepping in the stratosphere

Special discretization of horizontal pressure gradient

(apart from conventional method; Zängl 2012, MWR)

- **Precompute for each edge (velocity) point at level the grid layers into which the edge point would fall in the two adjacent cells**



dashed lines: main levels

pink: edge (velocity) points

blue: cell (mass) points

Discretization of horizontal pressure gradient

- **Reconstruct the Exner function at the mass points using a quadratic Taylor expansion, starting from the point lying in the model layer closest to the edge point**

$$\tilde{\pi}_c = \pi_c + \frac{\partial \pi_c}{\partial z}(z_e - z_c) + \frac{1}{2}\frac{g}{c_p \theta_v^2}\frac{\partial \theta_v}{\partial z}(z_e - z_c)^2$$

- **Note: the quadratic term has been approximated using the hydrostatic equation to avoid computing a second derivative**
- **Treatment at slope points where the surface is intersected:**

$$\left.\frac{\partial \pi}{\partial x}\right|_S = \left.\frac{\partial \pi}{\partial x}\right|_A + \left.\frac{g}{c_p \theta_v^2}\frac{\partial \theta_v}{\partial x}\right|_A (z_S - z_A)$$

Physics parameterizations

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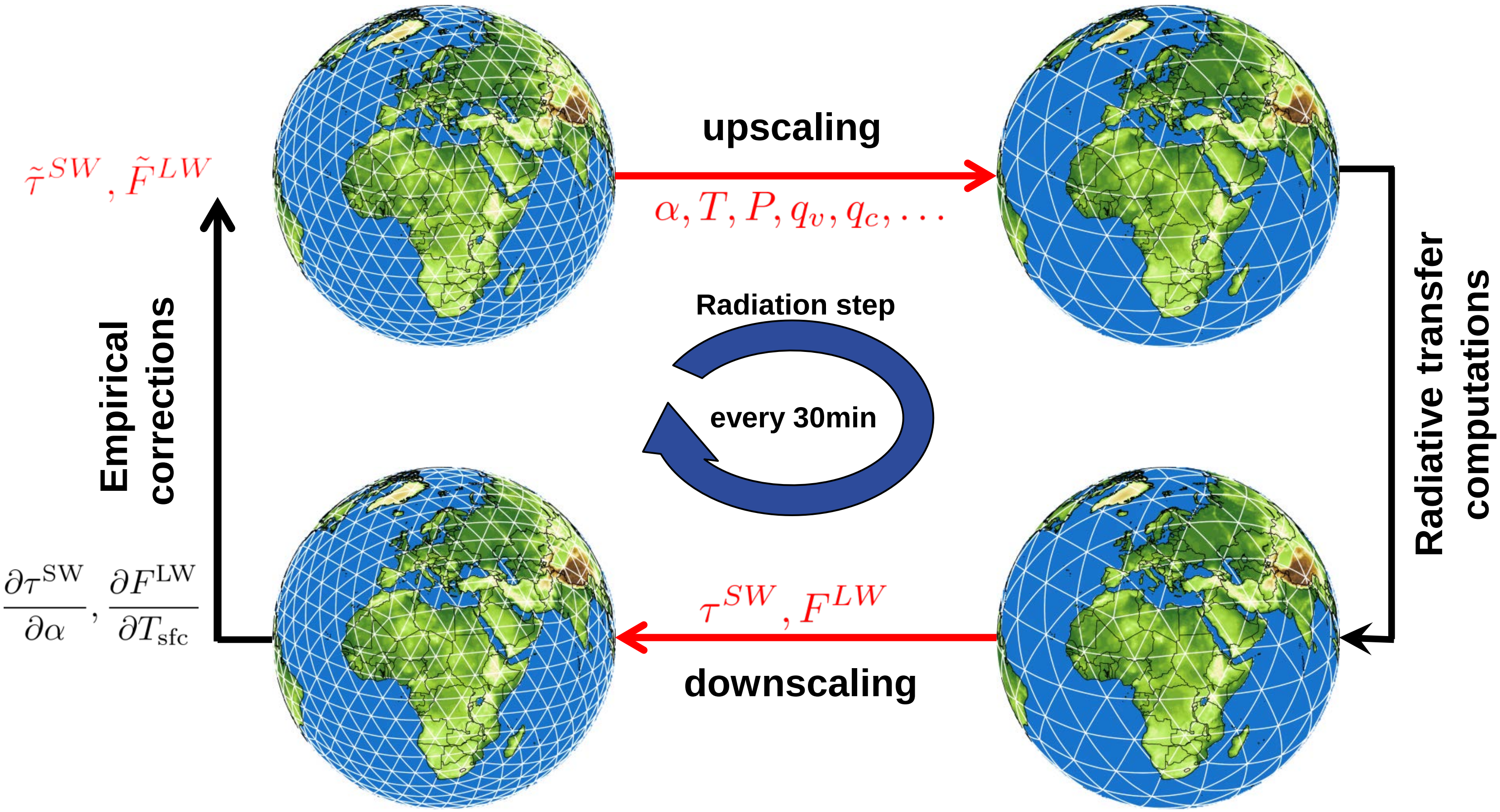
Process	Authors	Scheme	Origin
Radiation	Mlawer et al. (1997) Barker et al. (2002)	RRTM (later with McICA & McSI)	ECHAM6/IFS
	Ritter and Geleyn (1992)	δ two-stream	GME/COSMO
Non-orographic gravity wave drag	Scinocca (2003) Orr, Bechtold et al. (2010)	wave dissipation at critical level	IFS
Sub-grid scale orographic drag	Lott and Miller (1997)	blocking, GWD	IFS
Cloud cover	Doms and Schättler (2004)	sub-grid diagnostic	GME/COSMO
	Köhler et al. (new development)	diagnostic (later prognostic) PDF	ICON
Microphysics	Doms and Schättler (2004) Seifert (2010)	prognostic: water vapor, cloud water,cloud ice, rain and snow	GME/COSMO
Convection	Tiedtke (1989) Bechthold et al. (2008)	mass-flux shallow and deep	IFS
Turbulent transfer	Raschendorfer (2001)	prognostic TKE	COSMO
	Brinkop and Roeckner (1995)	prognostic TKE	ECHAM6/IFS
	Neggers, Köhler, Beljaars (2010)	EDMF-DUALM	IFS
Land	Heise and Schrodin (2002), Helmert, Mironov (2008, lake)	tiled TERRA + FLAKE + multi-layer snow	GME/COSMO
	Raddatz, Knorr	JSBACH	ECHAM6

Physics-dynamics coupling

- **Fast-physics processes: incremental update in the sequence: saturation adjustment, transfer scheme, surface scheme, boundary layer / turbulence, cloud microphysics, saturation adjustment**
- **Slow-physics processes (convection, cloud cover diagnosis, radiation, orographic blocking, sub-grid-scale gravity waves): tendencies are added to the right-hand side of the velocity and Exner pressure equation**
- **Diabatic heating rates related to phase changes and radiation are consistently treated at constant volume**
- **Option for reduced radiation grid with special domain decomposition to minimize day/night load imbalance**

Reduced radiation grid

- Hierarchical structure of the triangular mesh is very favourable for calculating physical processes (e.g. radiative transfer) with different spatial resolution compared to dynamics.



Advection scheme by H. Miura (Mon. Wea. Rev., 2007)

$$\overline{\rho q}_i^{n+1} \Delta z_i = \overline{\rho q}_i^{n} \Delta z_i - \frac{1}{A_i^{n+1}} \sum_{e=1}^{3} \vec{F}_{ie} \cdot \vec{n}_{ie} \quad \text{, with} \quad \vec{F}_{ie} = \left(\iint_{A_{ie}} \Delta z \rho q \, \mathrm{d}A \right) \cdot \vec{\hat{n}}_{ie}$$

$\vec{n}_{ie}$, $\vec{\hat{n}}_{ie}$: Unit normal pointing outward of A_i and A_{ie}, respectively

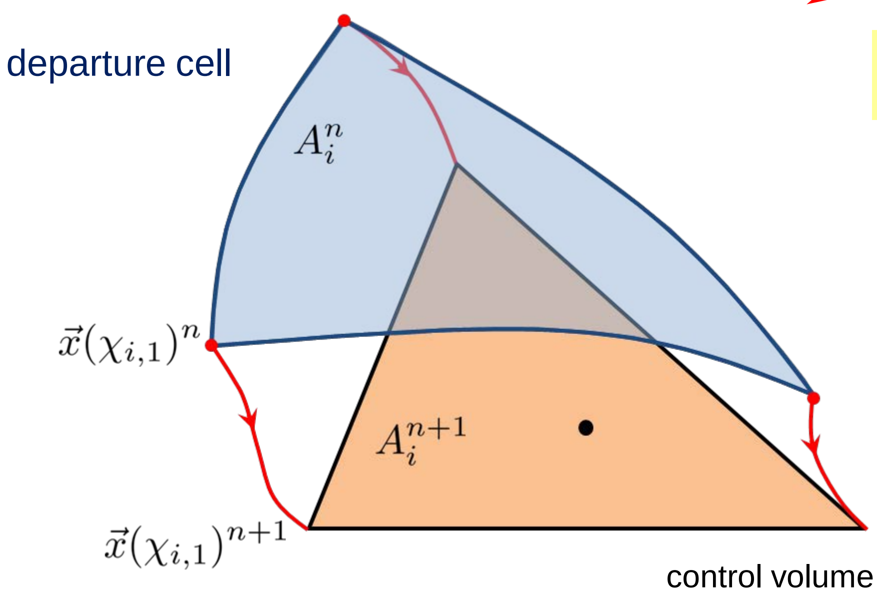
equivalent

Continuity equation in semi-Lagrangian view:

$$A_i^{n+1} \Delta z_i \, \overline{\rho q}_i^{n+1} = A_i^{n} \Delta z_i \, \overline{\rho q}_{A_i^n}^{n}$$

Integrate over departure cell A_i^n

$$\overline{\rho q}_i^{n+1} = \frac{1}{A_i^{n+1}} \iint_{A_i^n} \rho^n(x,y) q^n(x,y) \mathrm{d}A$$



Error norms, Gaussian hills

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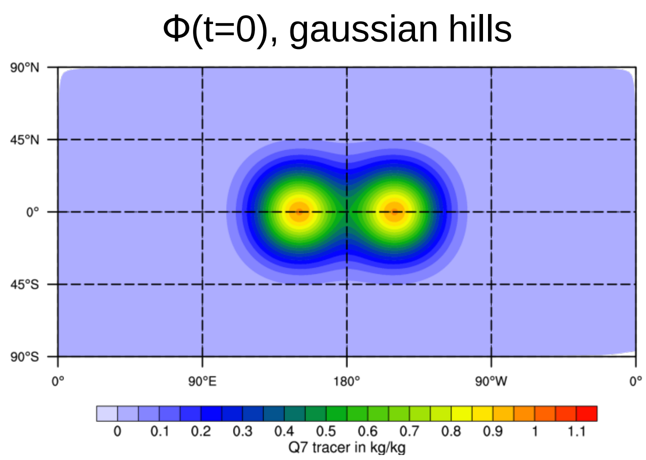
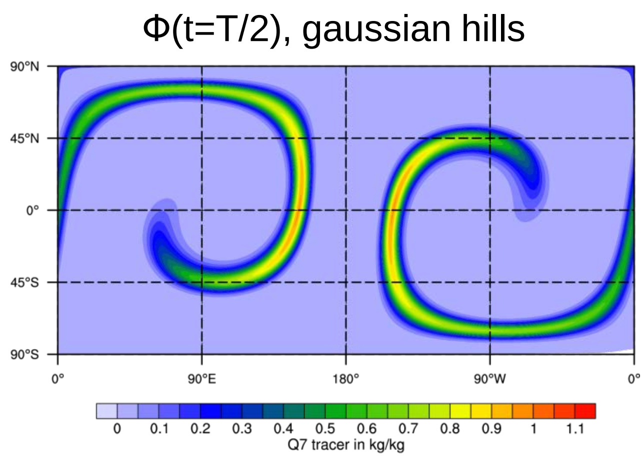
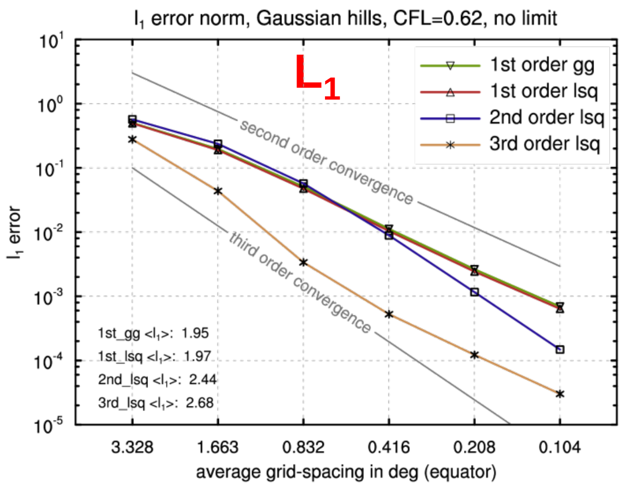
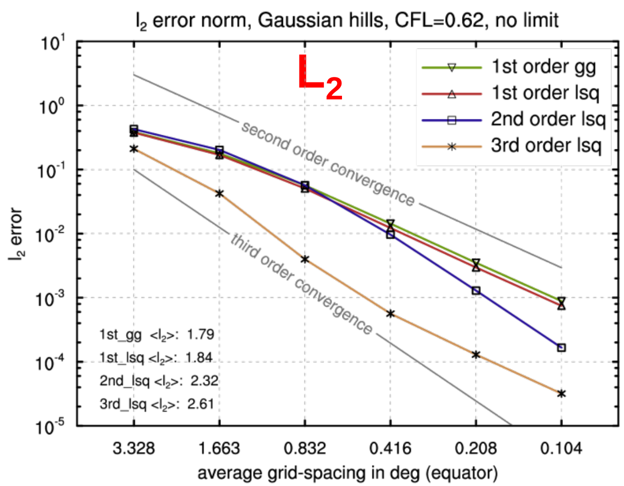
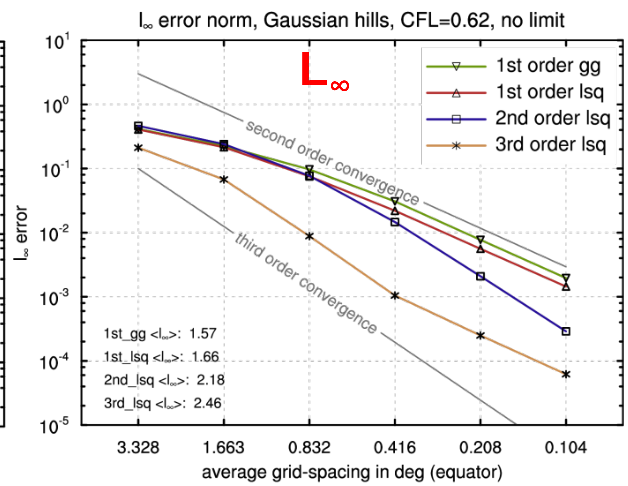




- no limiter
- CFL≈0.62/0.31







Error norms, Gaussian hills (no limiter vs. limiter)

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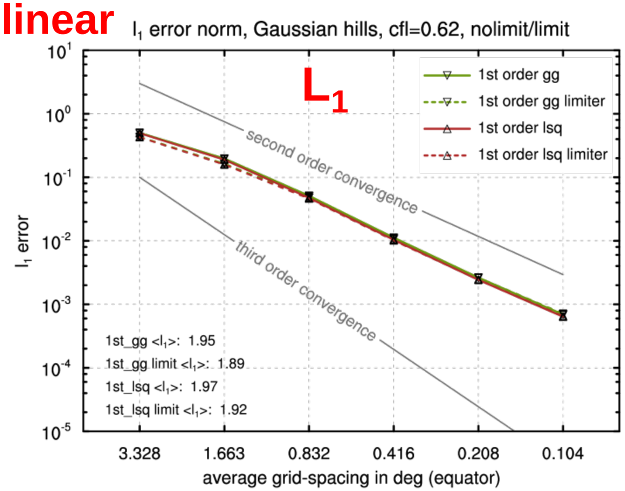
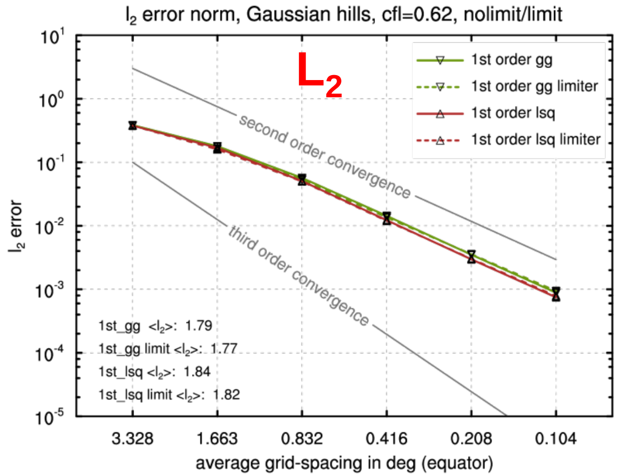
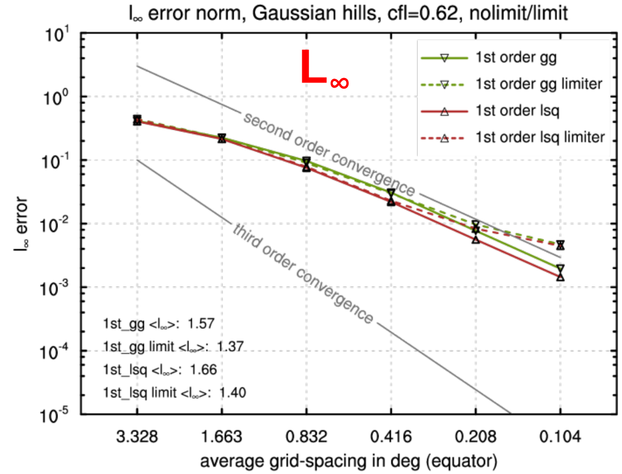
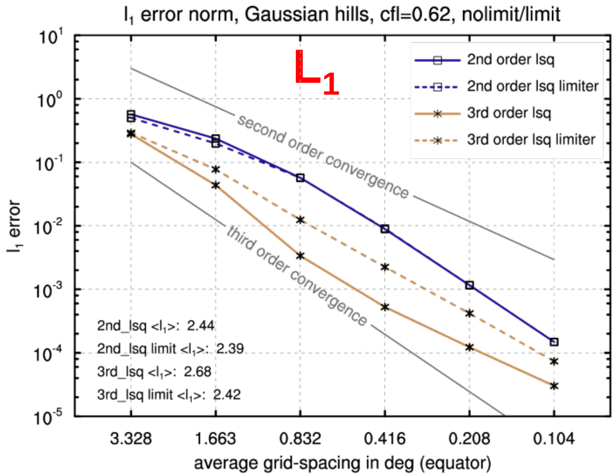
linear

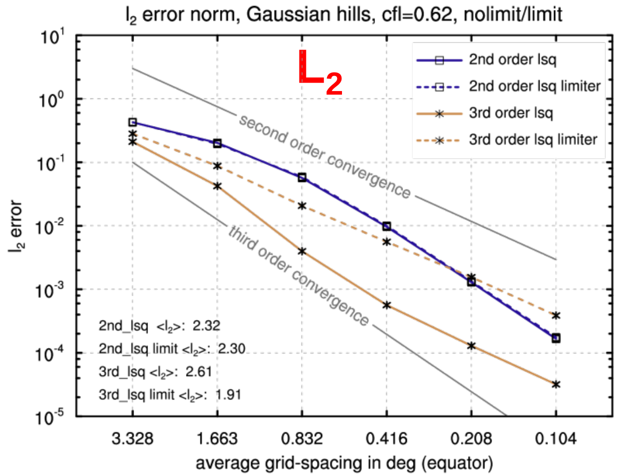


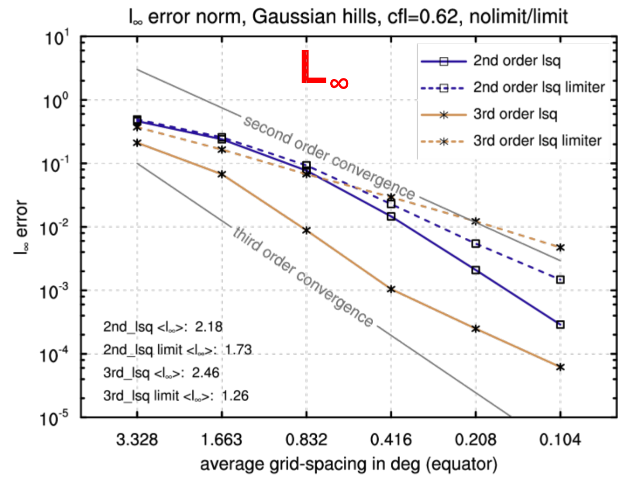




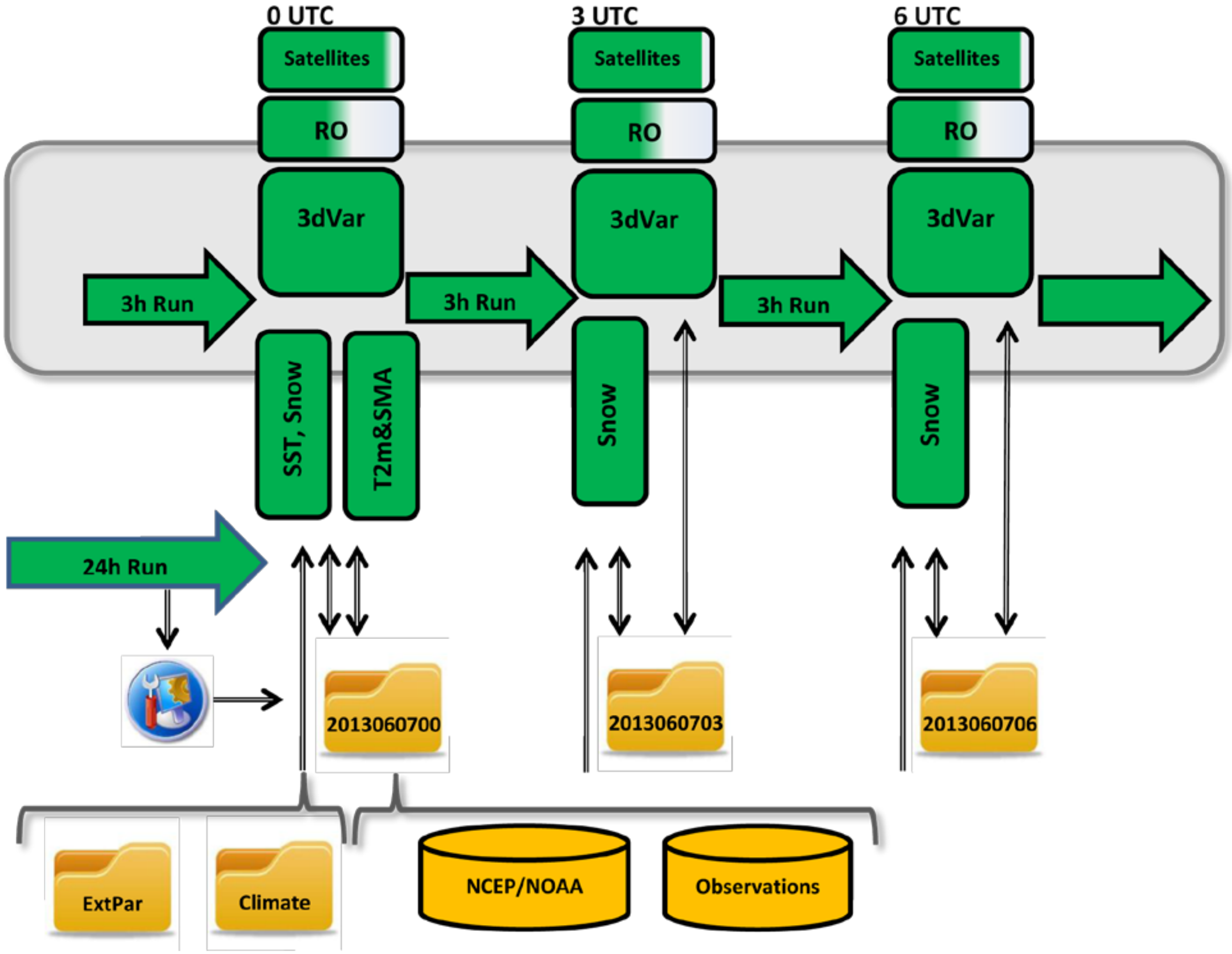
quadratic, cubic







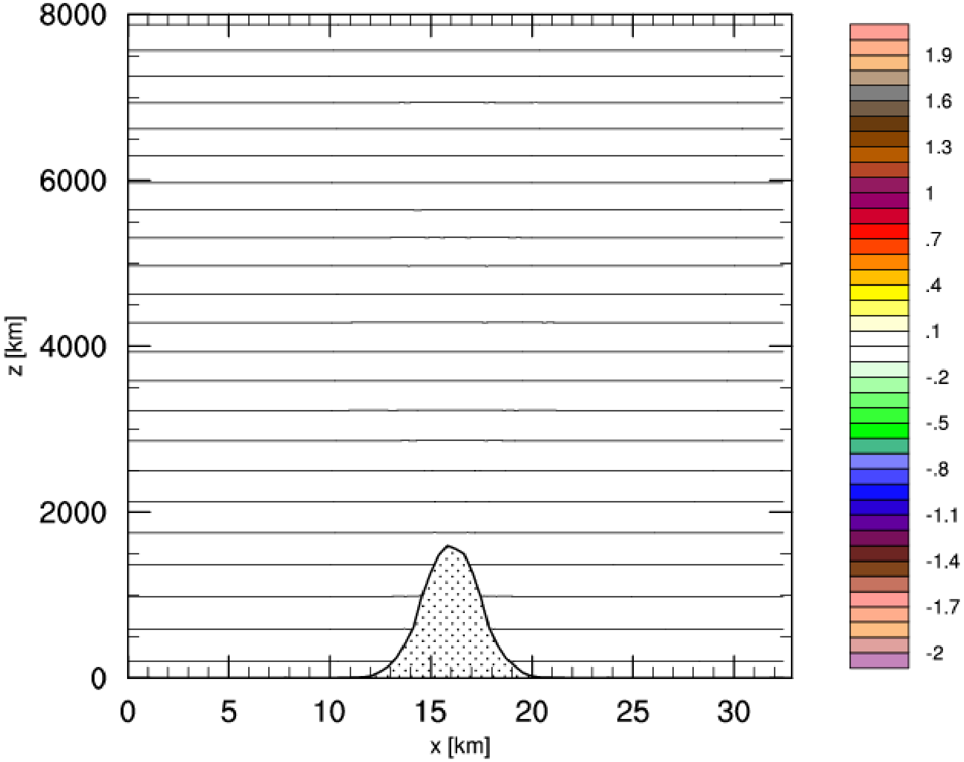
The coupled forecasting system with 3D-Var data assimilation (EnKF-DA is in preparation, but will likely be introduced as a second step)

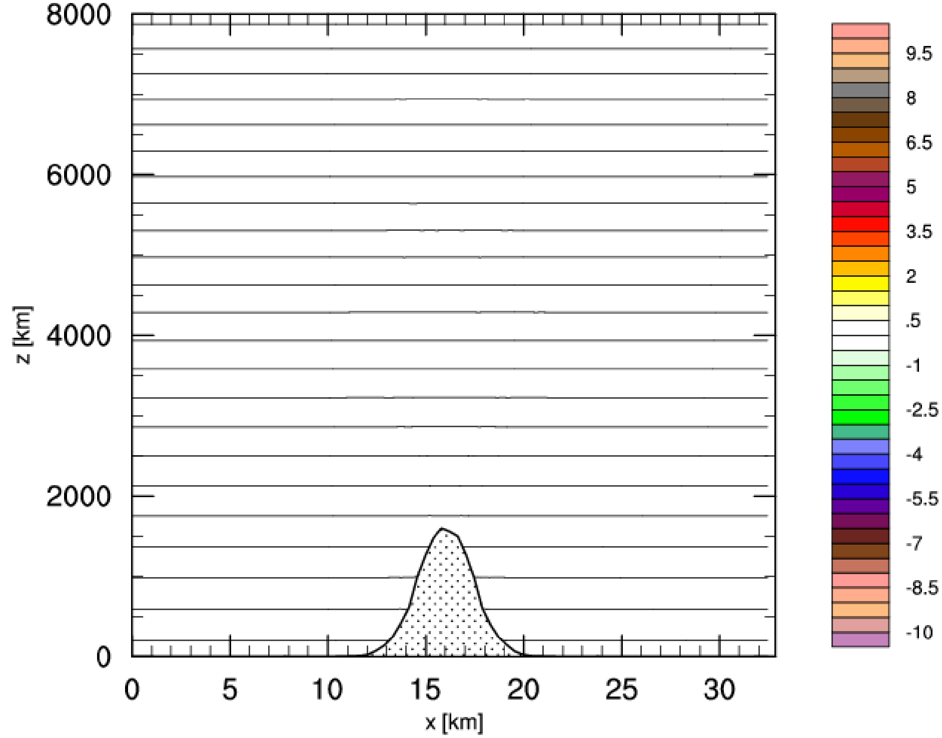


Selected experiments and results

- **Idealized tests with an isolated circular Gaussian mountain, mesh size 300 m: atmosphere-at-rest and generation of nonhydrostatic gravity waves**
- **Schär mountain test: consistency of metric terms**
- **Jablonowski-Williamson baroclinic wave test with/without grid nesting**
- **DCMIP tropical cyclone test with/without grid nesting**
- **Real-case tests with interpolated IFS analysis data**

conventional pressure gradient discretization



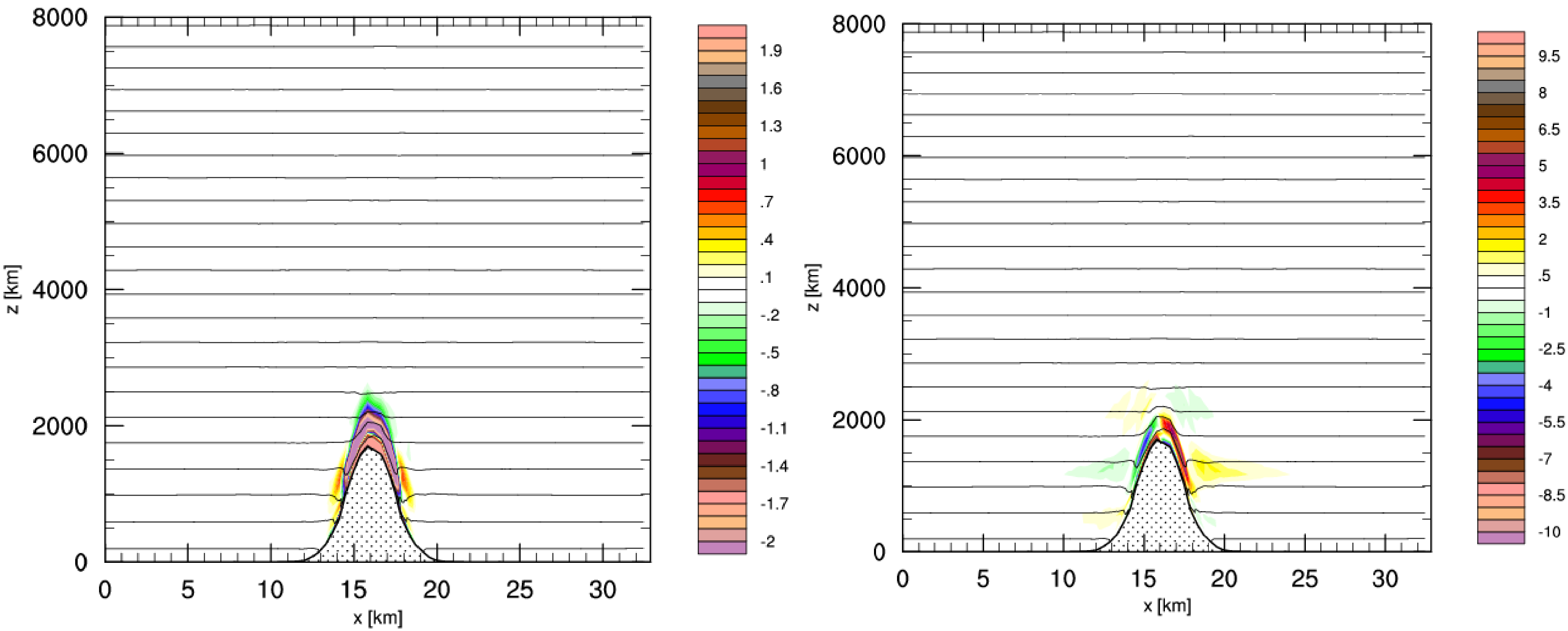


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

mountain height: 1.75 km, isothermal atmosphere at rest

maximum slope 0.74 (36.5°)

conventional pressure gradient discretization

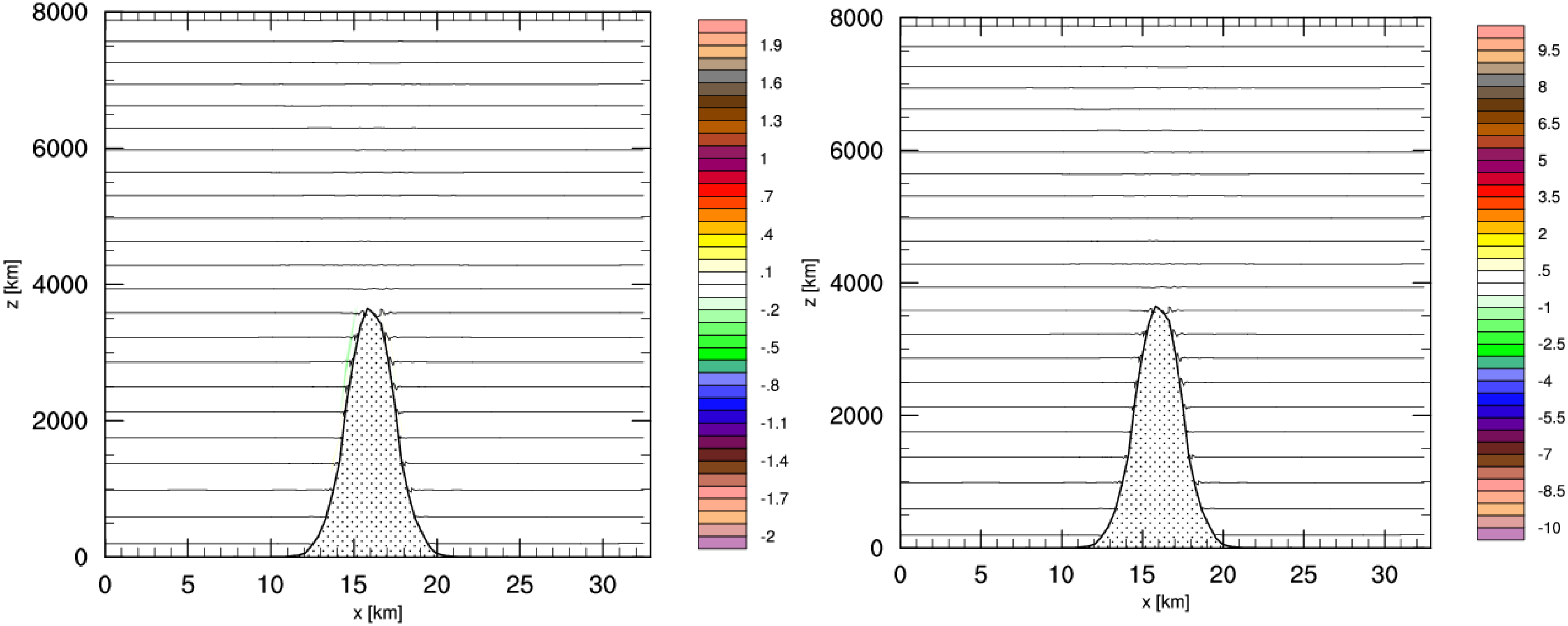


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

mountain height: 1.85 km, isothermal atmosphere at rest

maximum slope 0.78 (38°)

z-based pressure gradient discretization

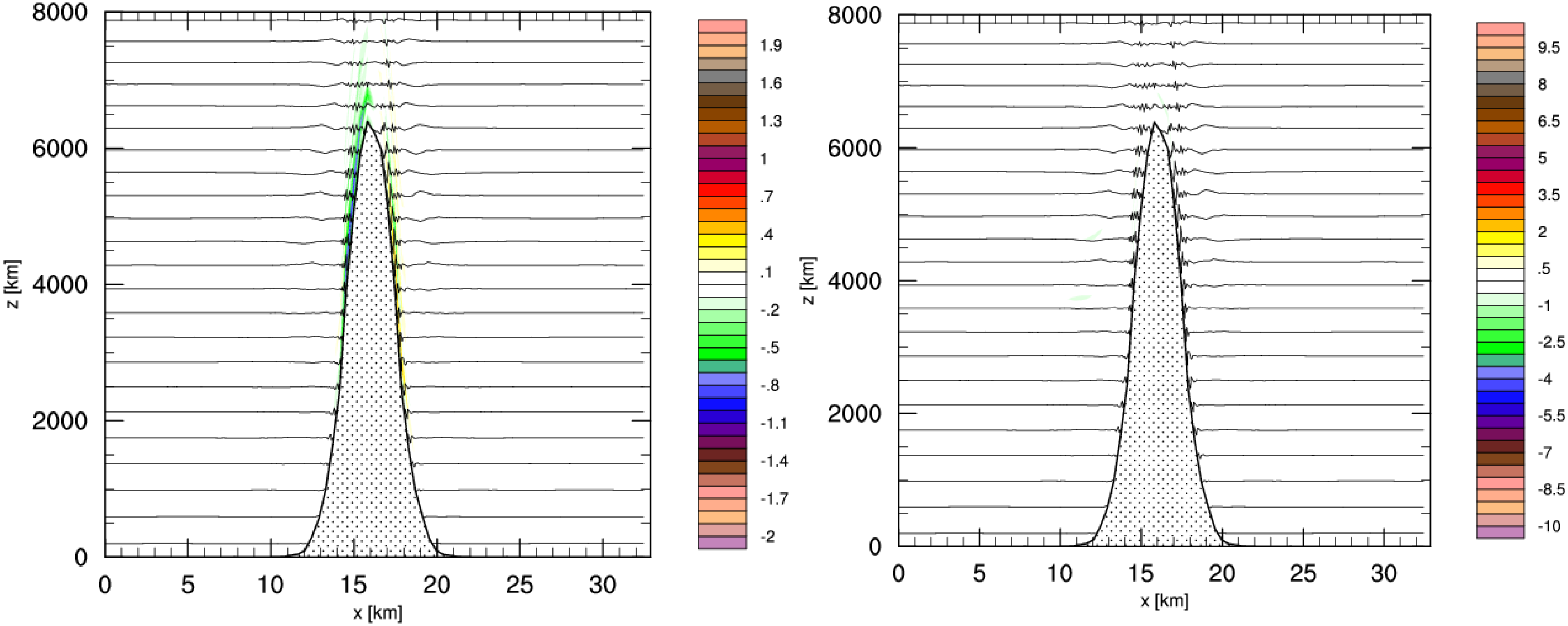


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

mountain height: 4.0 km, isothermal atmosphere at rest

maximum slope 1.7 (59°)

z-based pressure gradient discretization

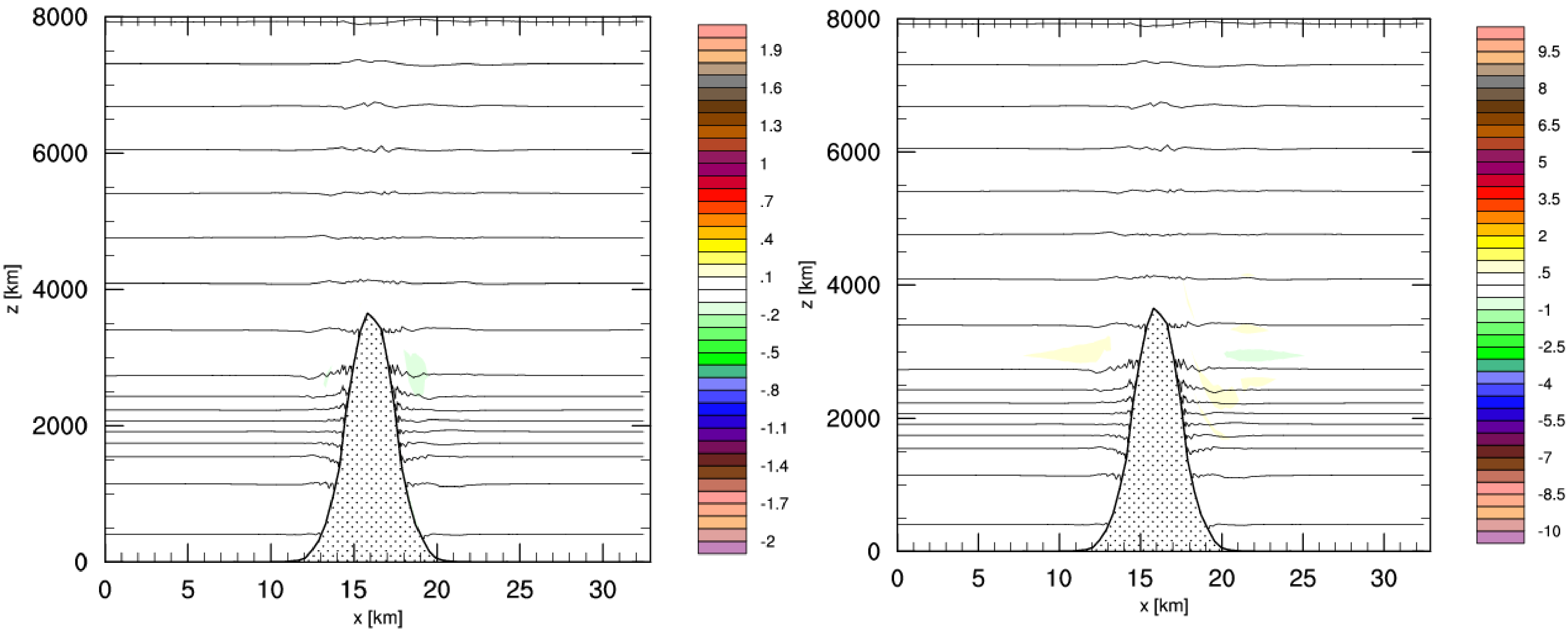


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

mountain height: 7.0 km, isothermal atmosphere at rest

maximum slope 3.0 (71°)

z-based pressure gradient discretization

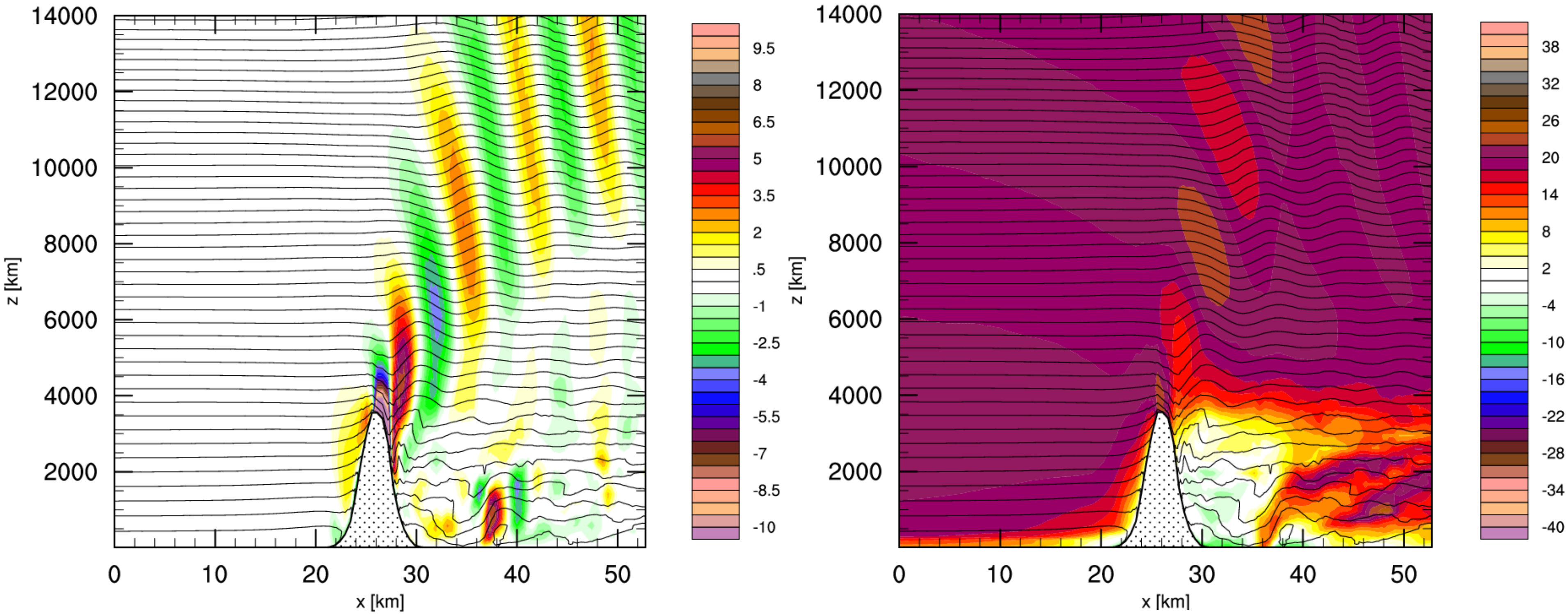


vertical wind speed (m/s) **potential temp. (contour interval 2 K)** **horizontal wind speed (m/s)**

mountain height: 4.0 km, multi-layer atmosphere at rest

maximum slope 1.7 (59°)

z-based pressure gradient discretization

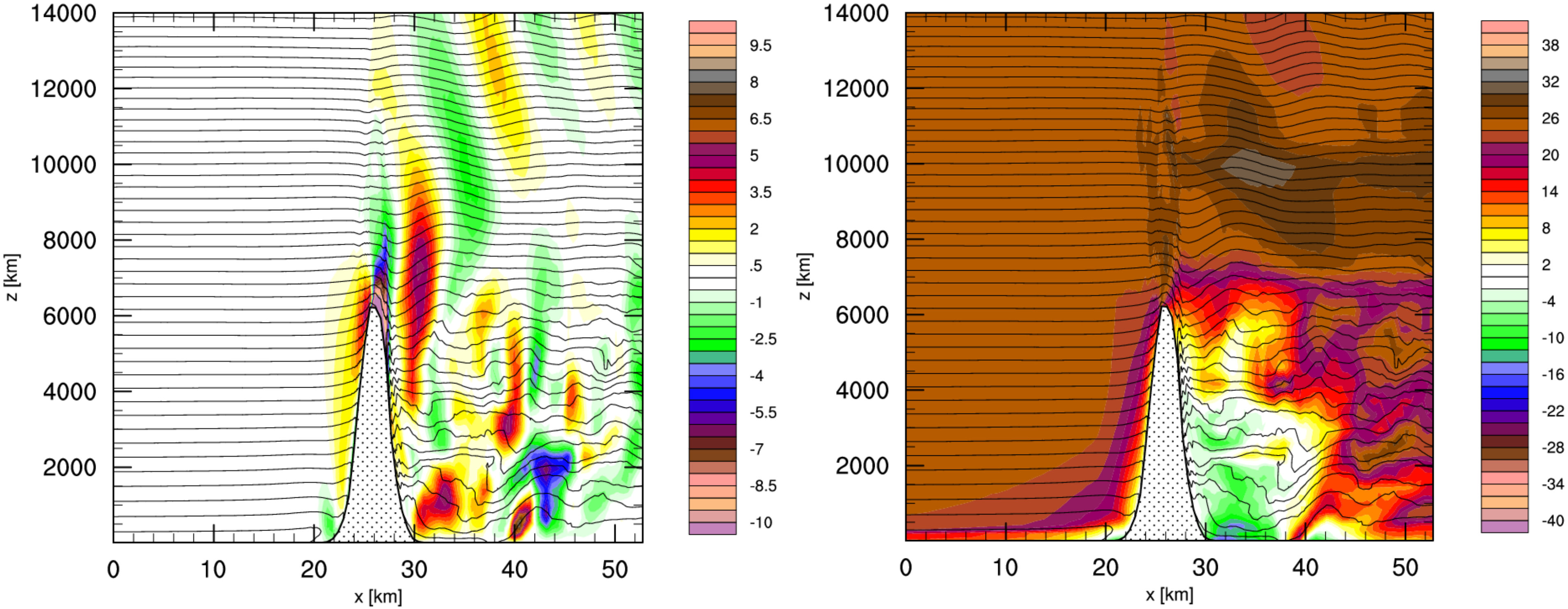


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

mountain height: 4.0 km, isothermal atmosphere with u_0 = 20 m/s

maximum slope 1.7 (59°)

z-based pressure gradient discretization

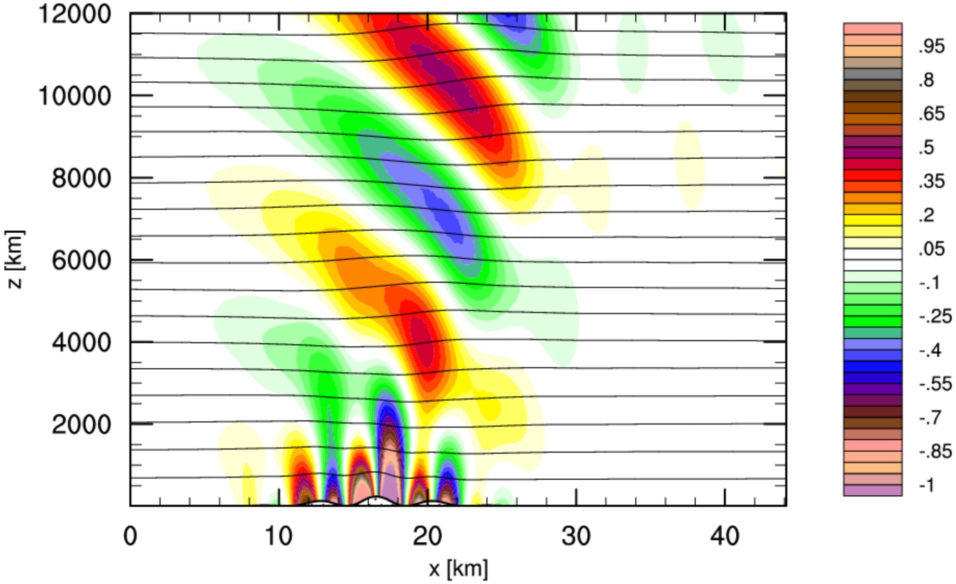


vertical wind speed (m/s) **potential temp. (contour interval 4 K)** **horizontal wind speed (m/s)**

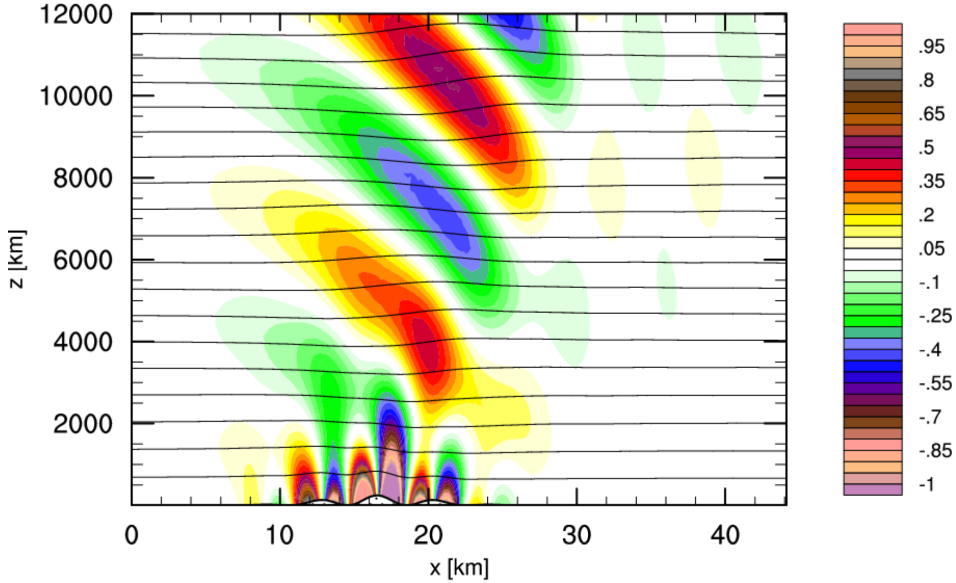
mountain height: 7.0 km, isothermal atmosphere with u_0 = 25 m/s

maximum slope 3.0 (71°)

Linear Schär mountain test, wind speed 10 m/s, mountain height 250 m: vertical wind speed (m/s) and potential temperature



mesh size 625 m



mesh size 312 m

Jablonowski-Wiliamson test, surface pressure (Pa) after 10 days

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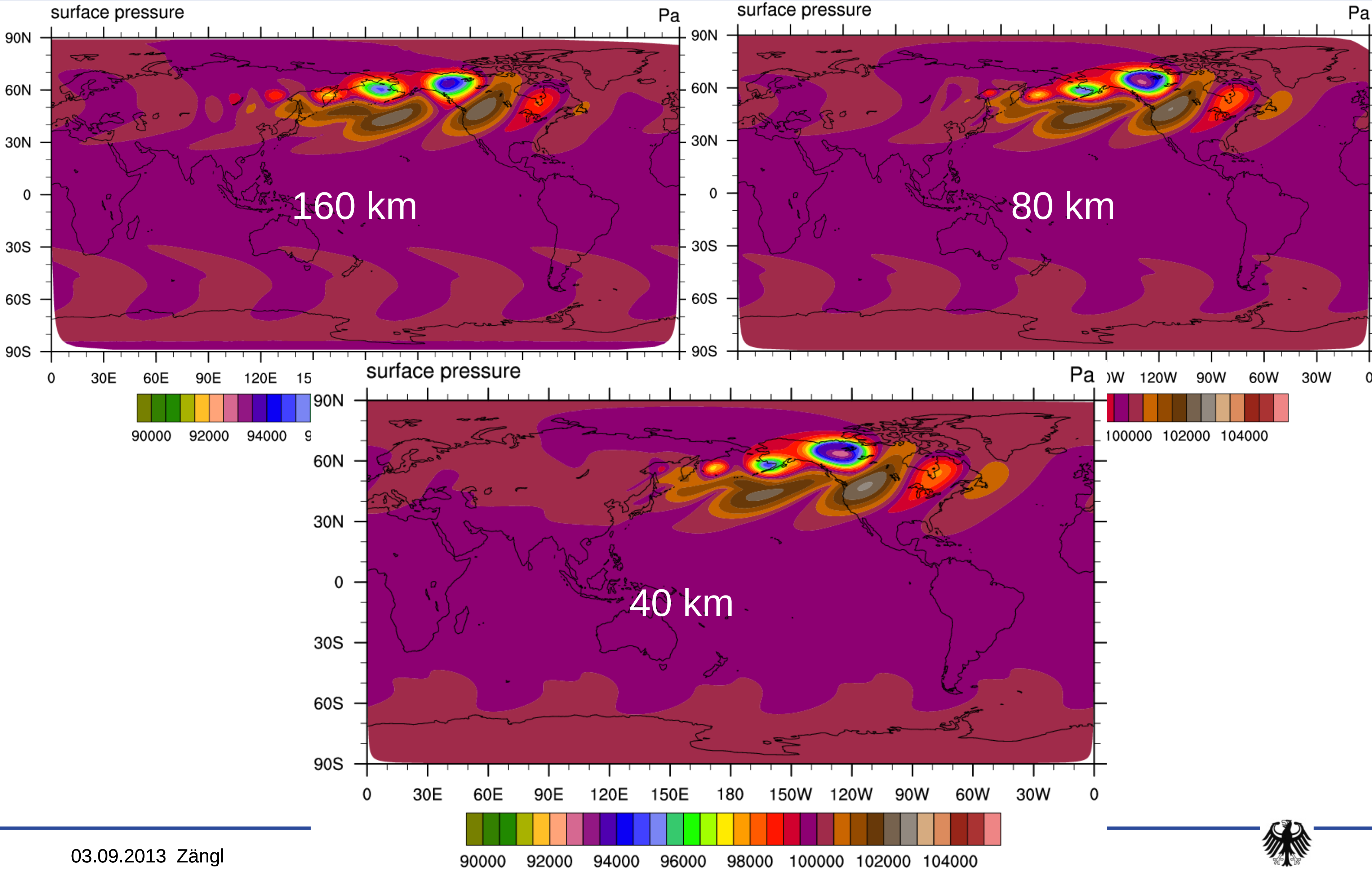

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Jablonowski-Wiliamson test, surface pressure (Pa) after 10 days

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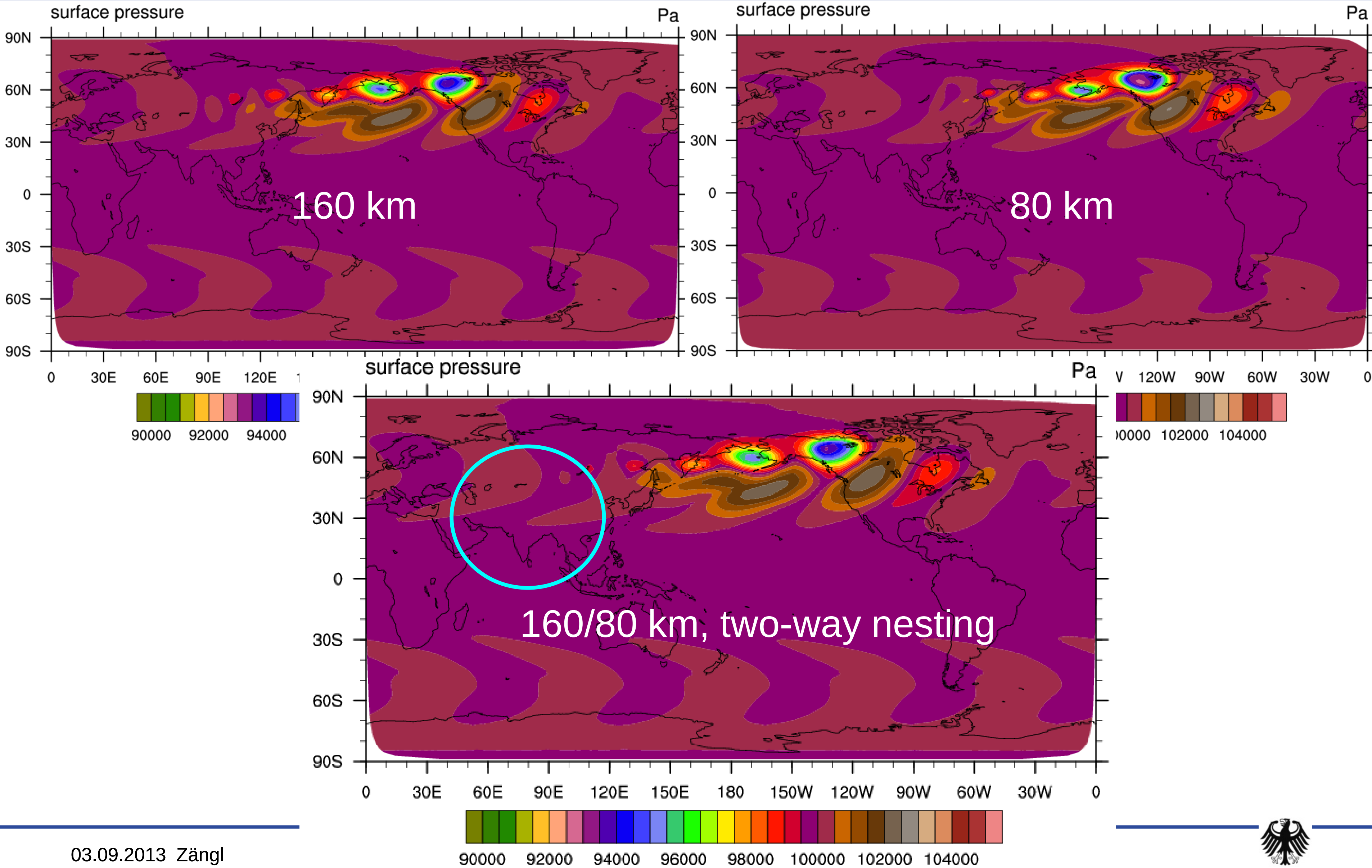
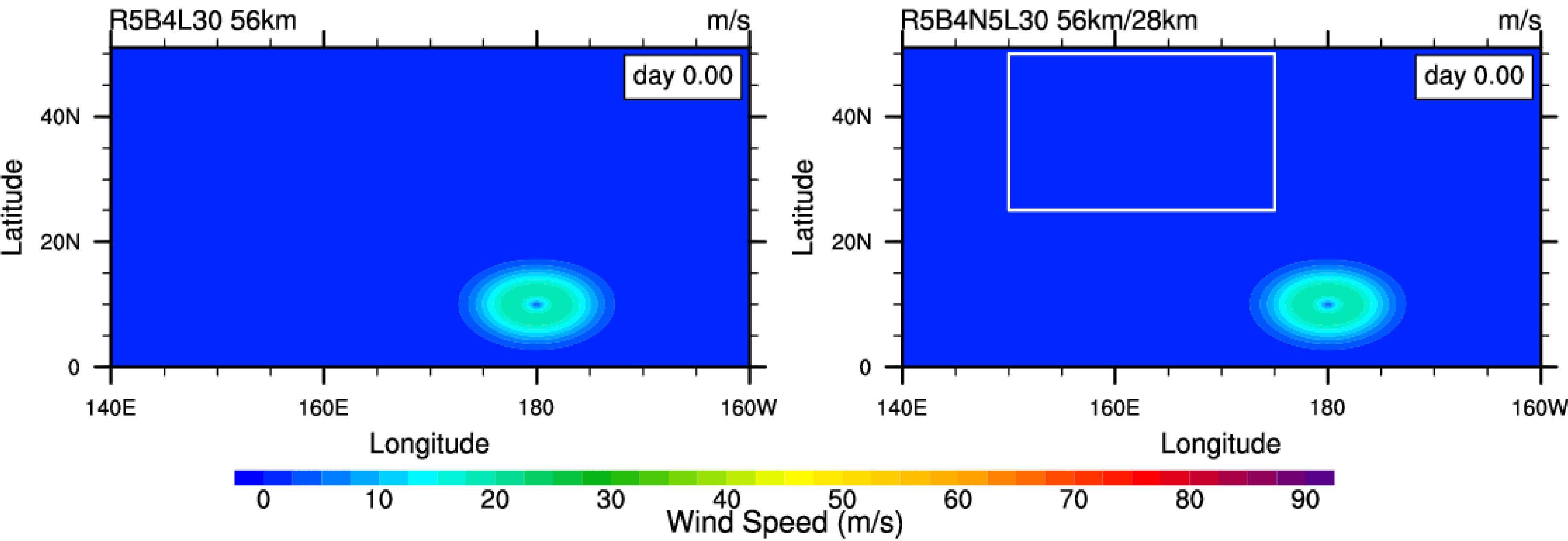


DCMIP tropical cyclone test with NWP physics schemes, evolution over 12 days



Absolute horizontal wind speed (m/s)

Left: single domain, 56 km; right: two-way nesting, 56 km / 28 km

Selected results of NWP test suite

- Real-case tests with interpolated IFS analysis data
- 7-day forecasts starting at 00 UTC of each day in January and June 2012
- Model resolution 40 km / 90 levels up to 75 km (no nesting applied in the experiment shown here)
- Reference experiment with GME40L60 with interpolated IFS data
- WMO standard verification on 1.5° lat-lon grid against IFS analyses; separately for January and June, and monthly averaged comparison against IFS analyses
- Physics package: RRTM with Köhler cloud cover scheme, COSMO-EU microphysics, Tiedtke-Bechtold convection, COSMO-EU turbulence scheme with minimum vertical diffusion coefficient of 0.2 m^2/s, retuning of SSO scheme with respect to GME settings

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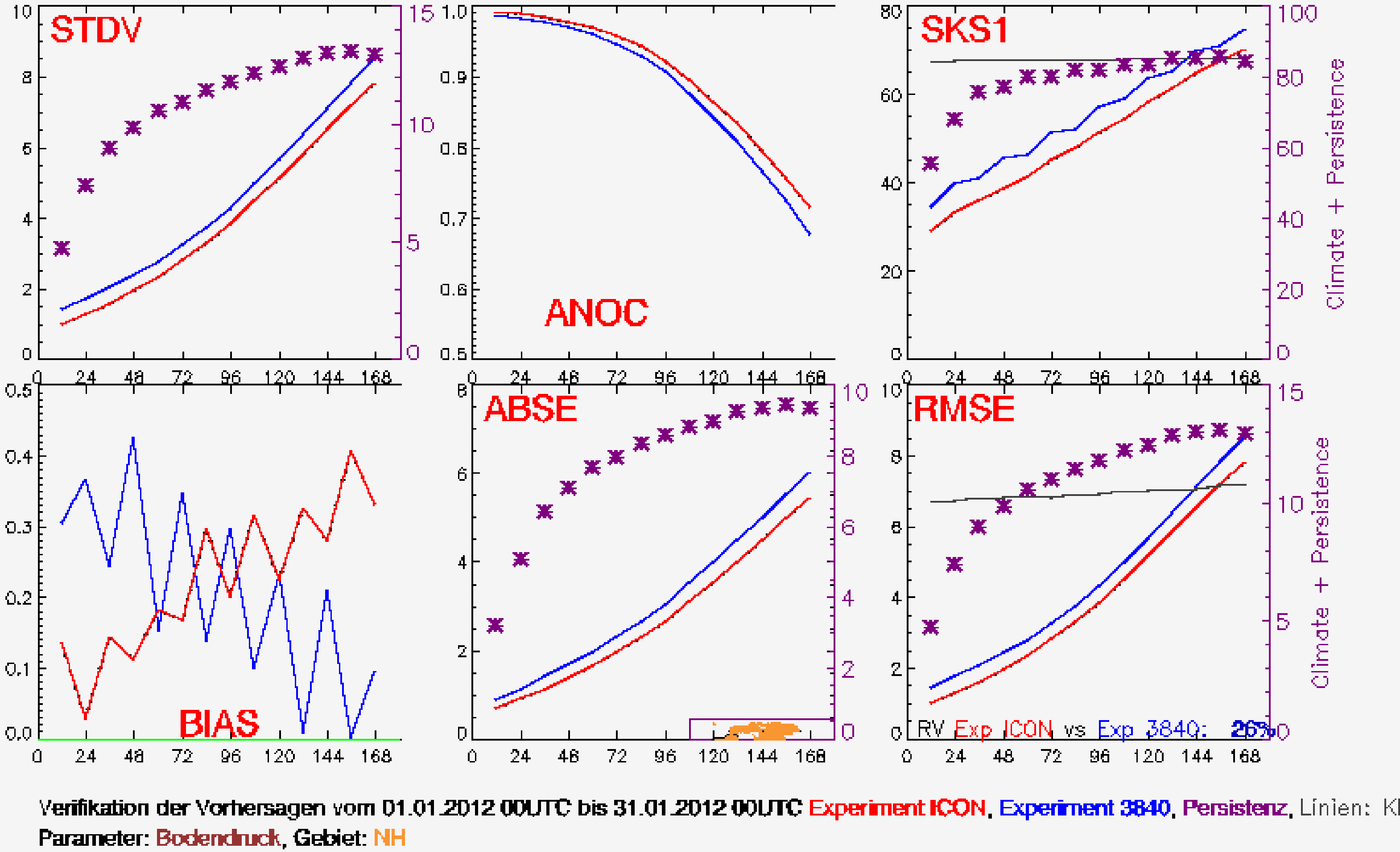
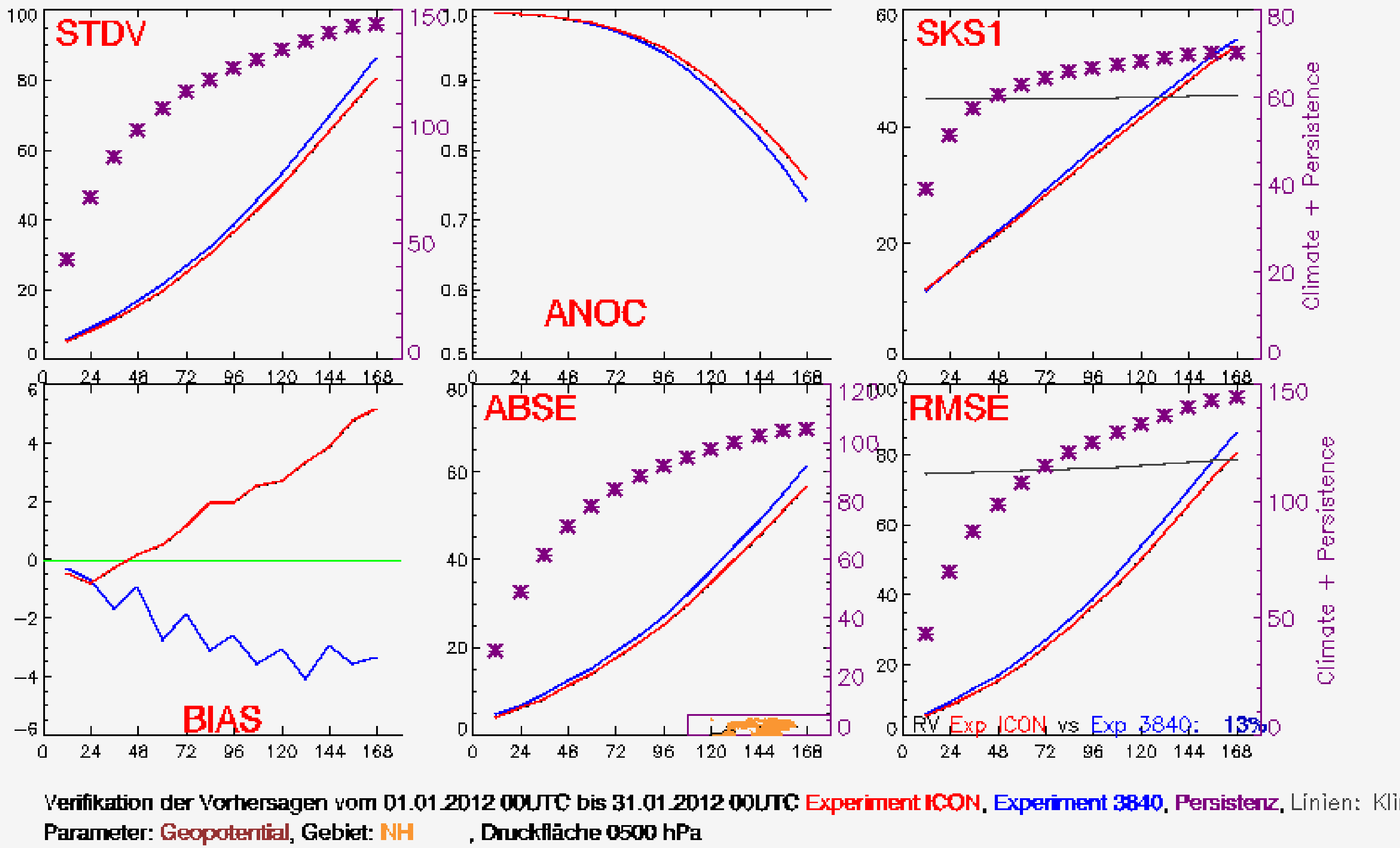
WMO standard verification against IFS analysis: sea-level pressure, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis



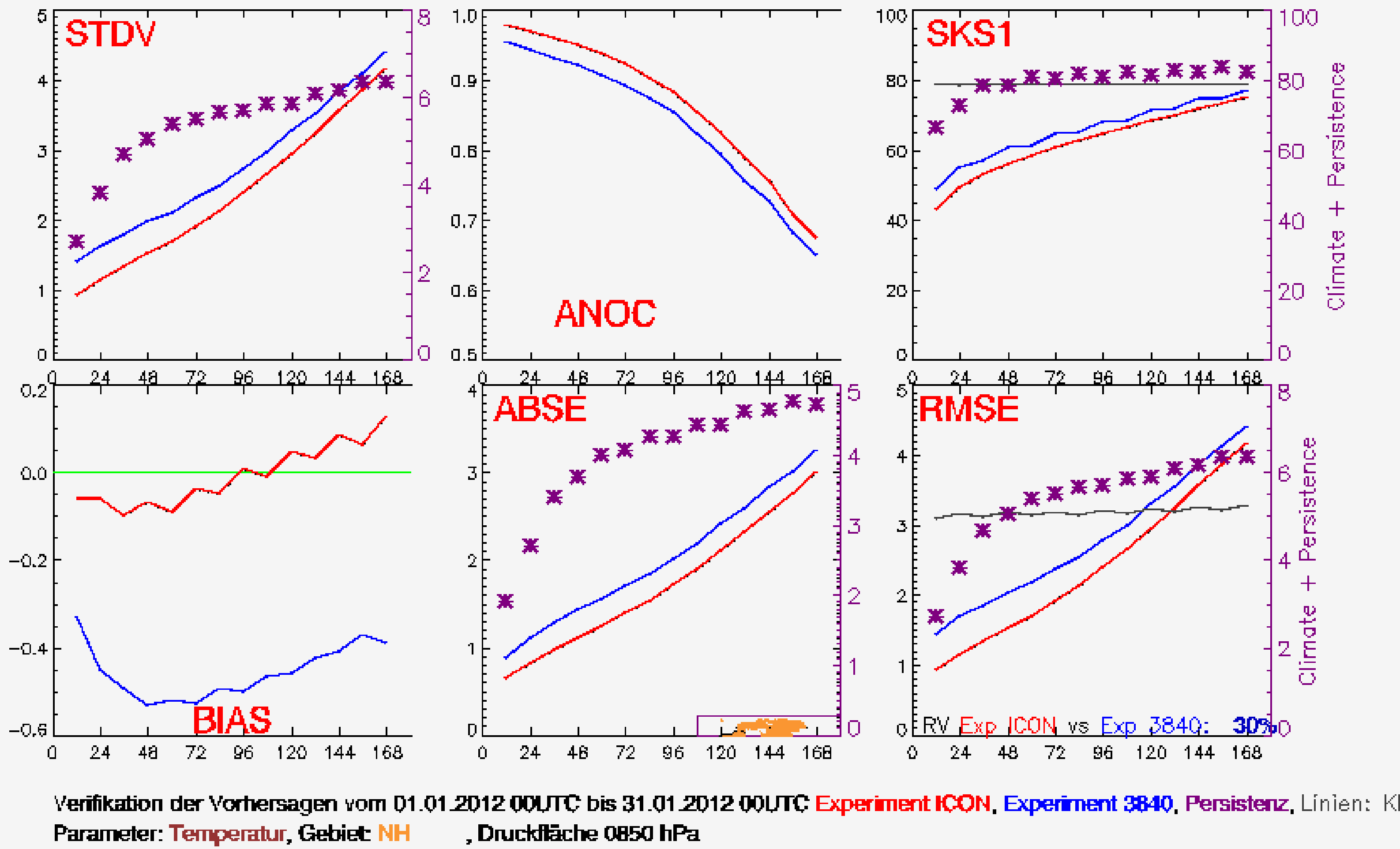
WMO standard verification against IFS analysis: 500 hPa geopotential, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis



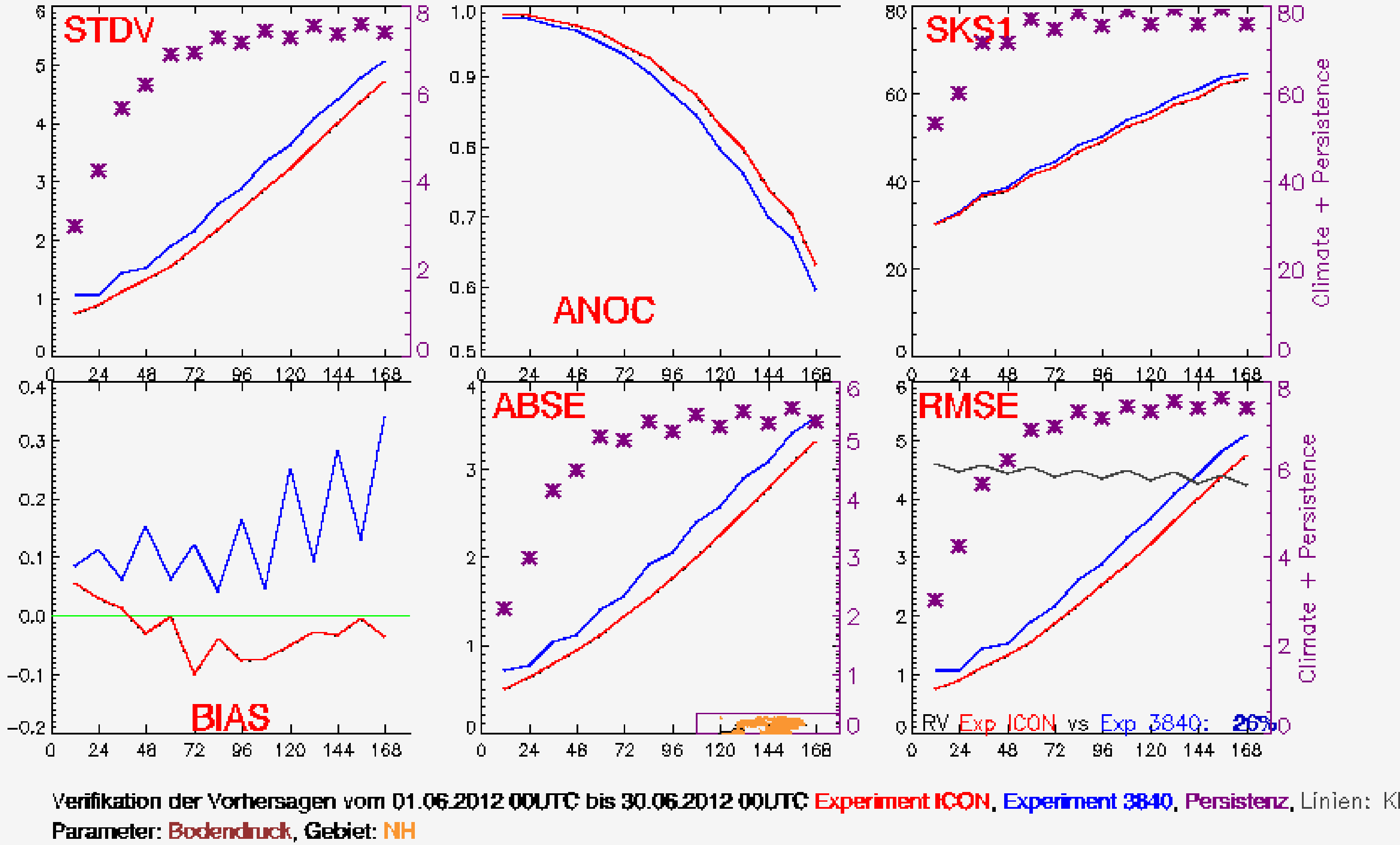
WMO standard verification against IFS analysis: 850 hPa temperature, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis



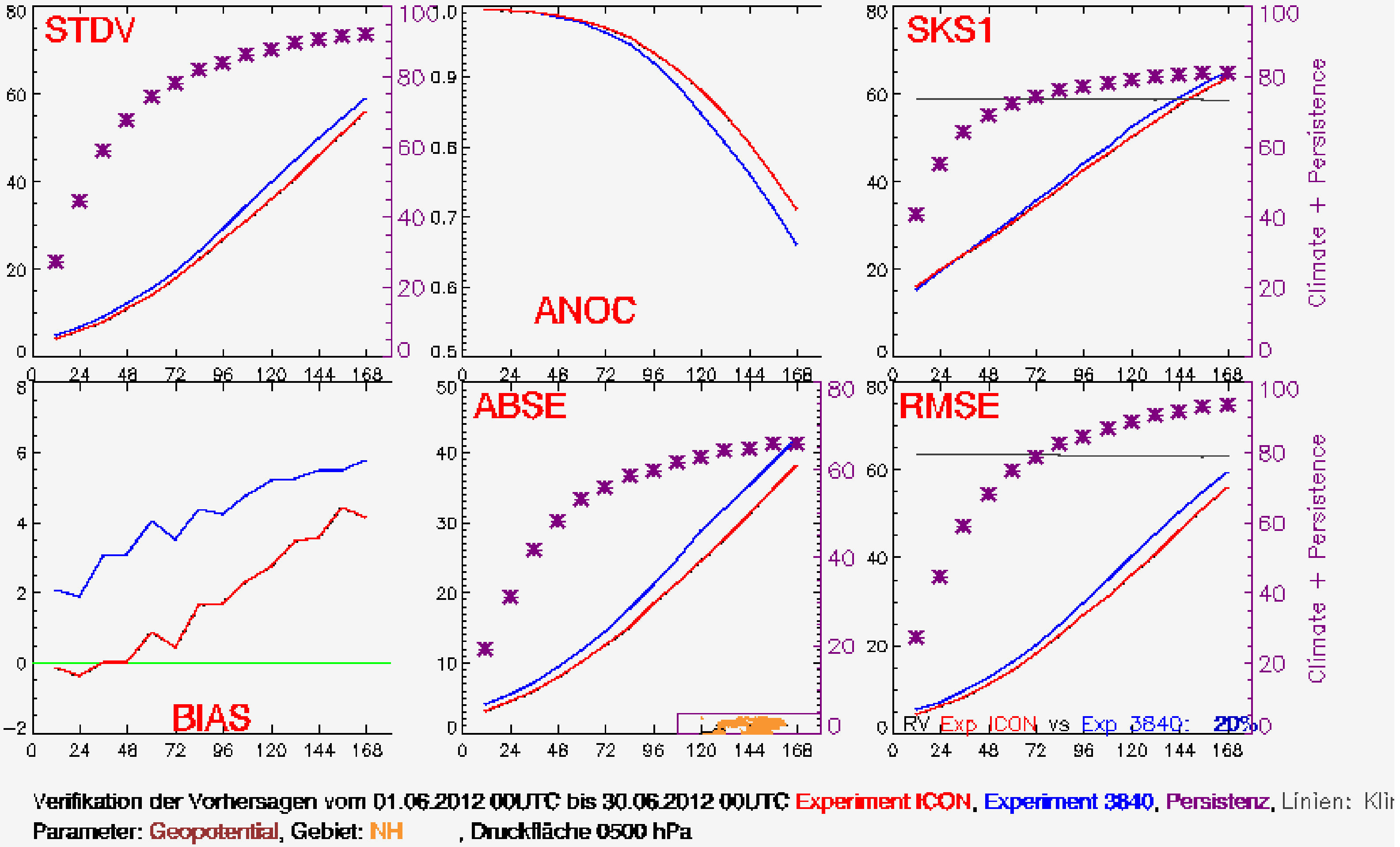
WMO standard verification against IFS analysis: sea-level pressure, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis



WMO standard verification against IFS analysis: 500 hPa geopotential, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis

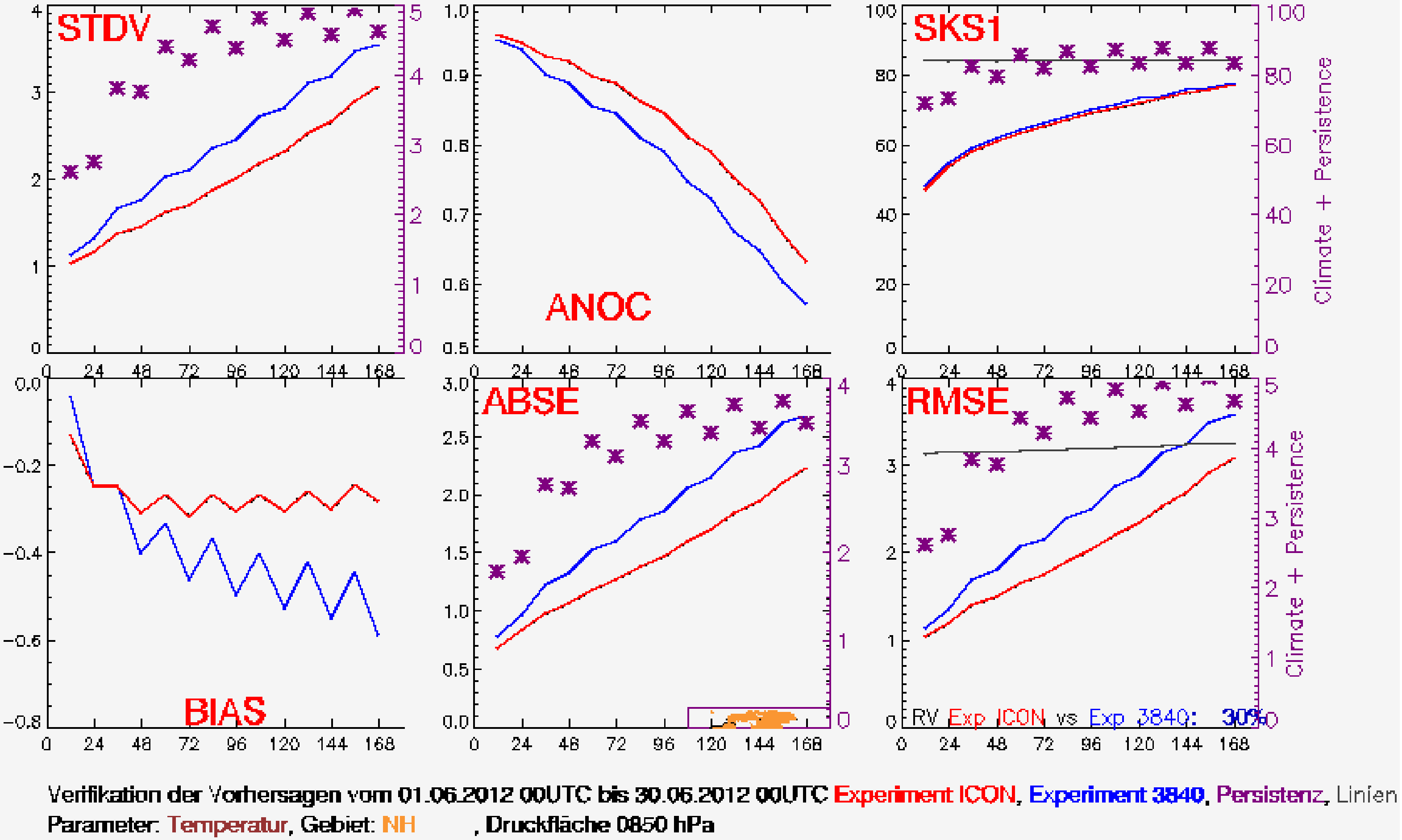


Max-Planck-Institut für Meteorologie

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

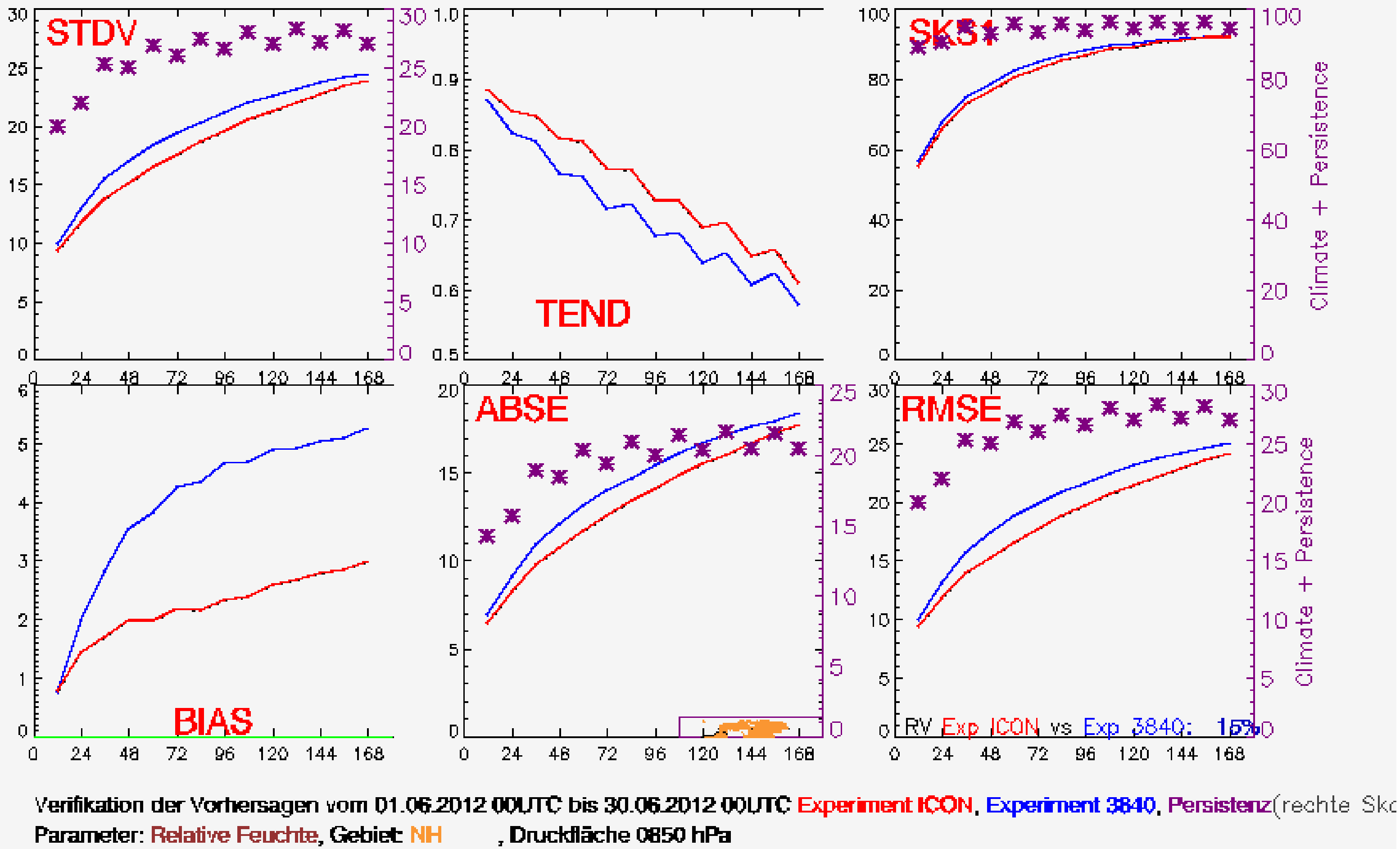
WMO standard verification against IFS analysis: 850 hPa temperature, NH

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis



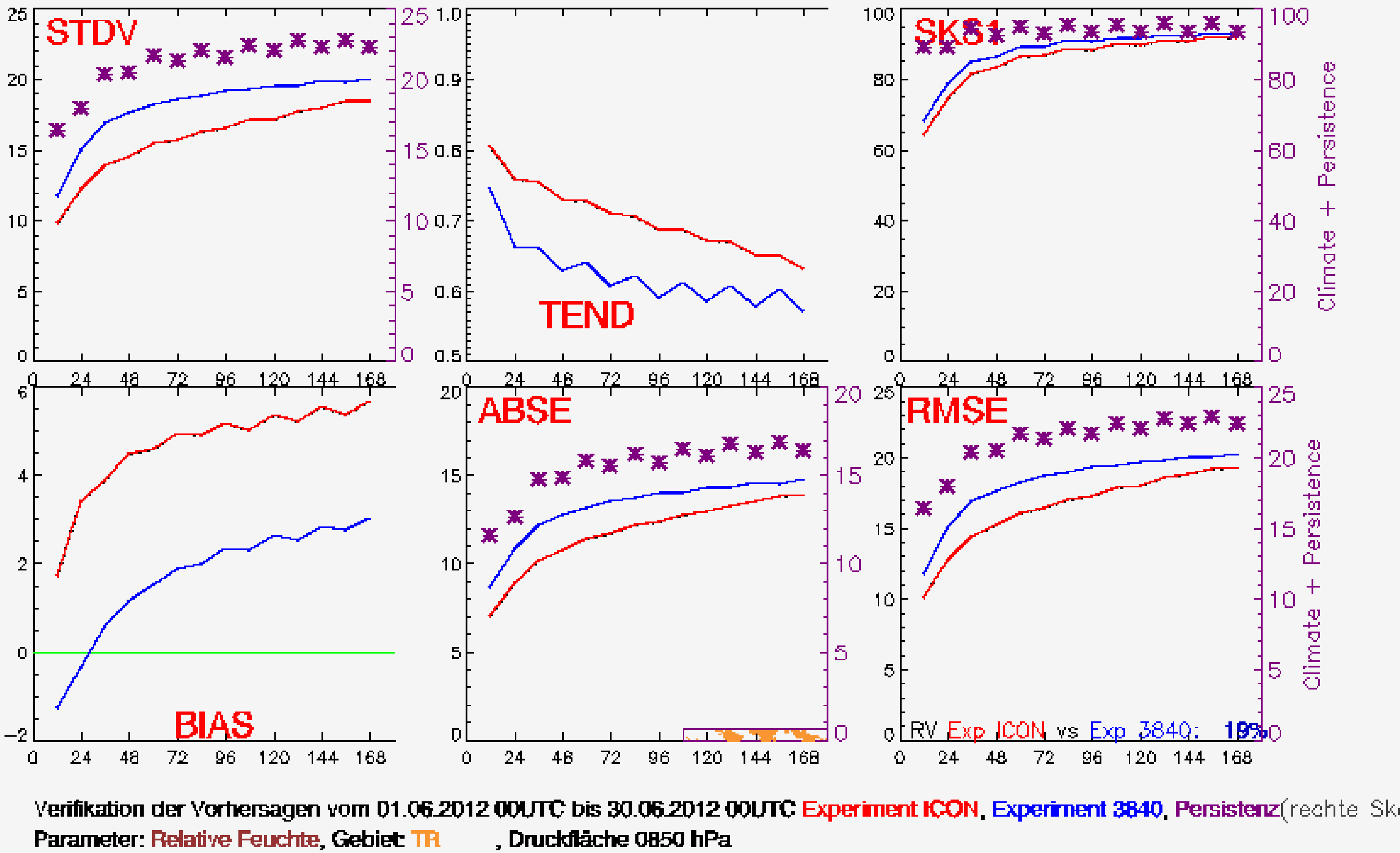
WMO standard verification against IFS analysis: 850 hPa humidity, NH

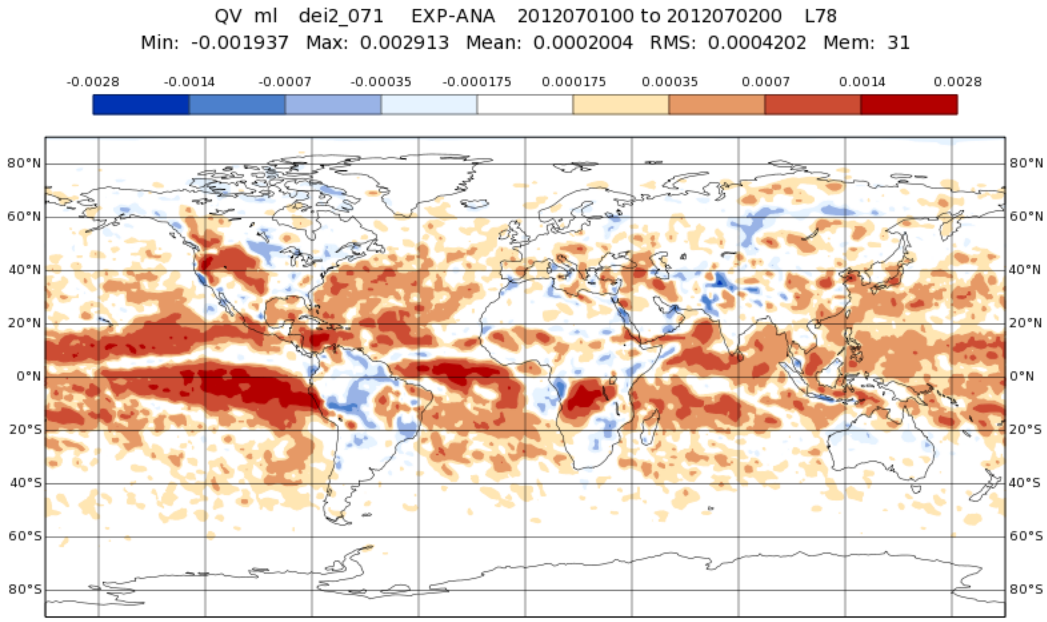
blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis

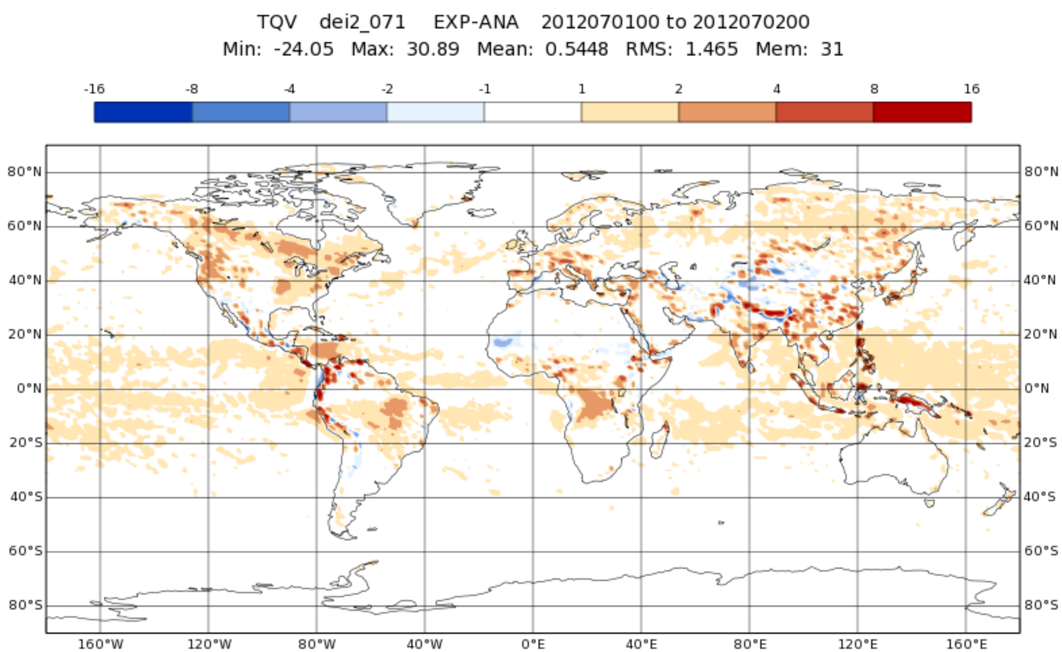


WMO standard verification against IFS analysis: 850 hPa humidity, Tropics

blue: GME 40 km with IFS analysis, red: ICON 40 km with IFS analysis





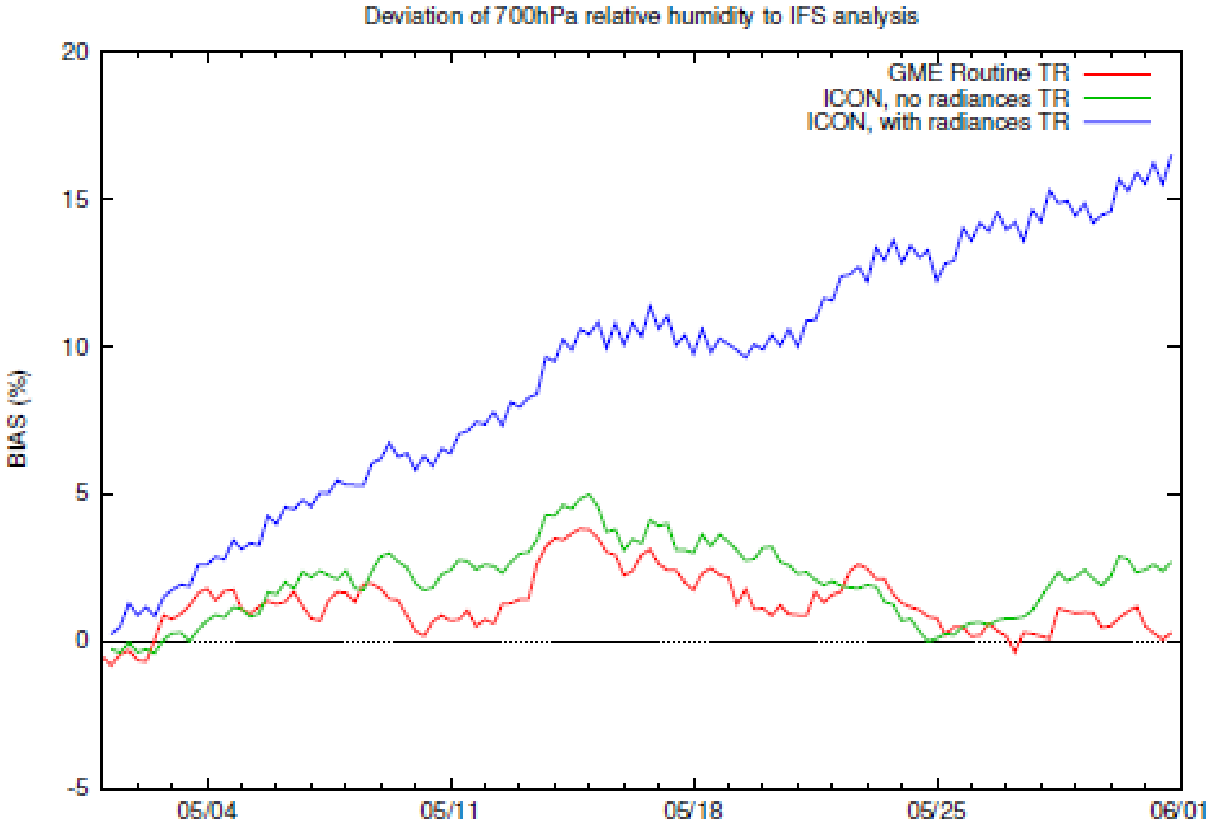


Average over 30 1-day ICON (80 km mesh size) forecasts compared to IFS analyses, July 2012

top: QV (ICON – IFS-ANA) at model level 78/90, about 1500 m AGL

bottom: integrated QV (ICON – IFS-ANA; kg/m²)

Currently encountered problem: Runaway feedback in combination with assimilation of satellite radiances



RH @ 700 hPa, tropics (20°S – 20°N)

blue: ICON with radiances

green: ICON without radiances

red: GME operational setup

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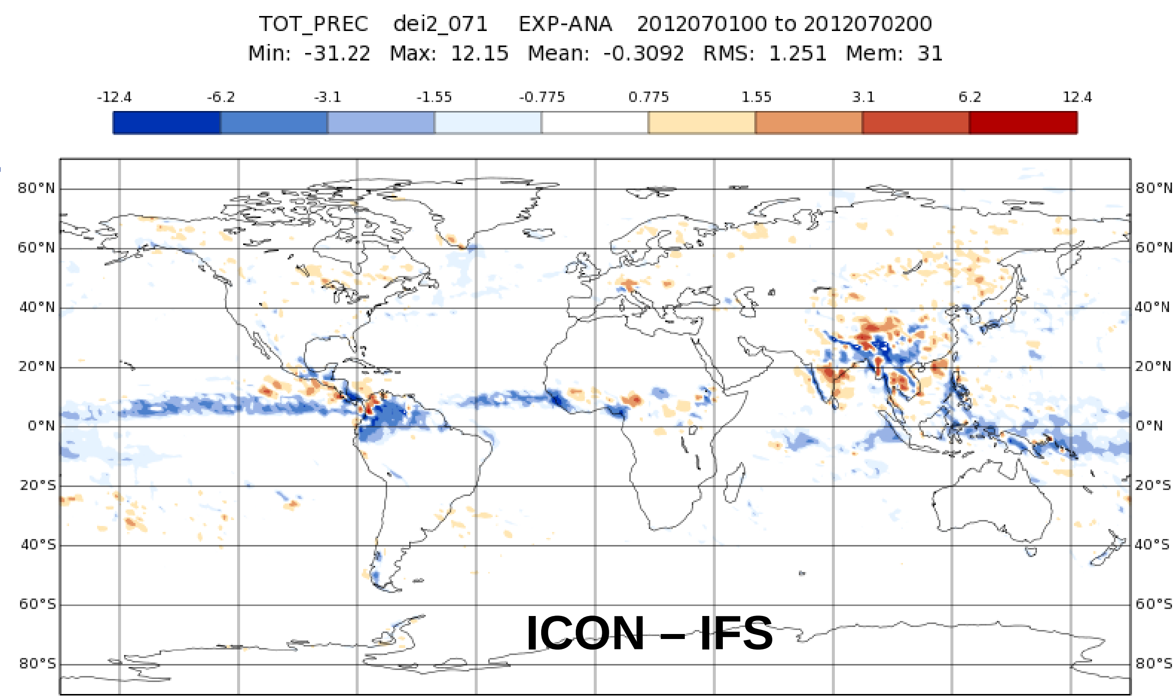
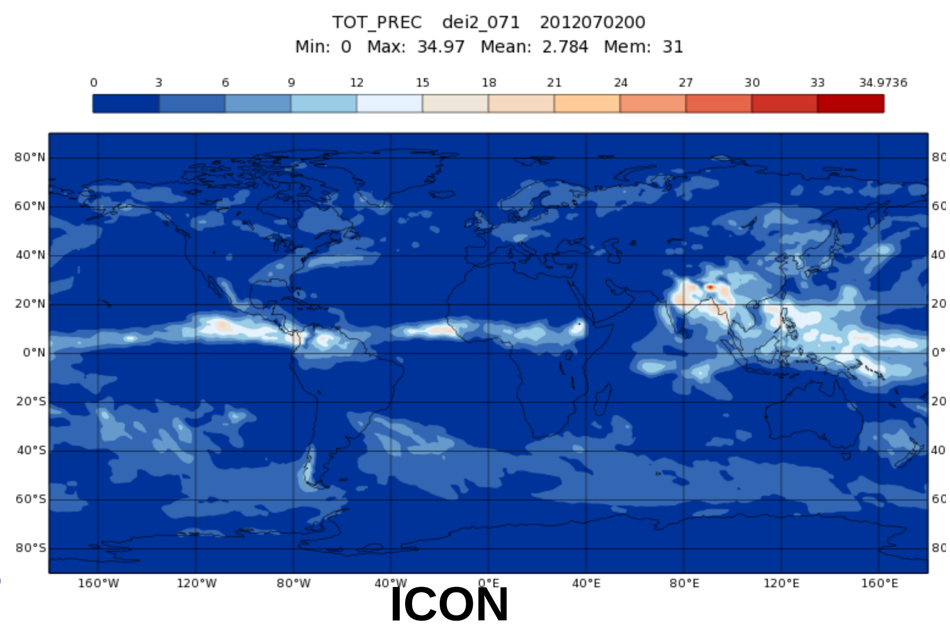
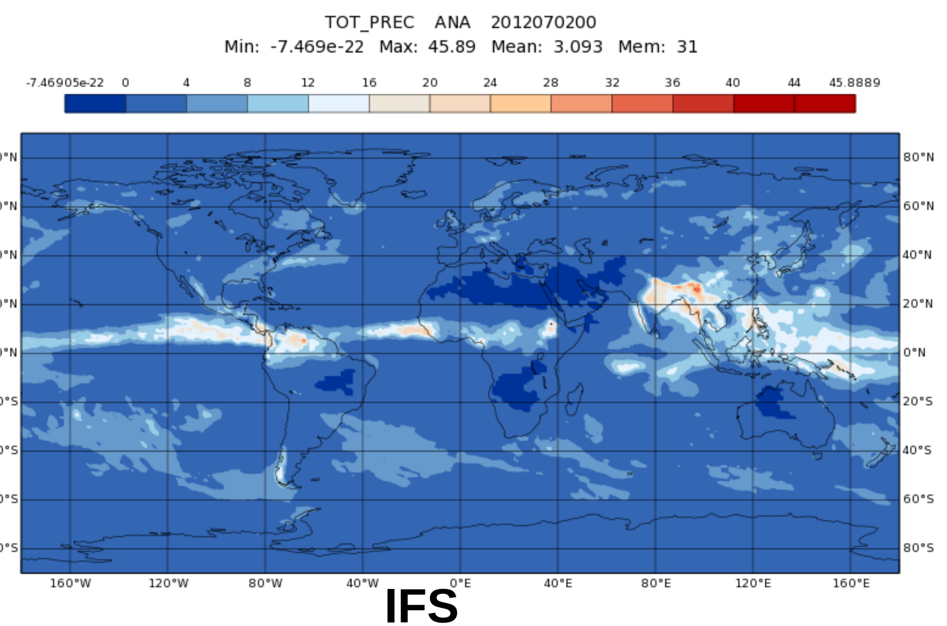
Total precipitation (mm)

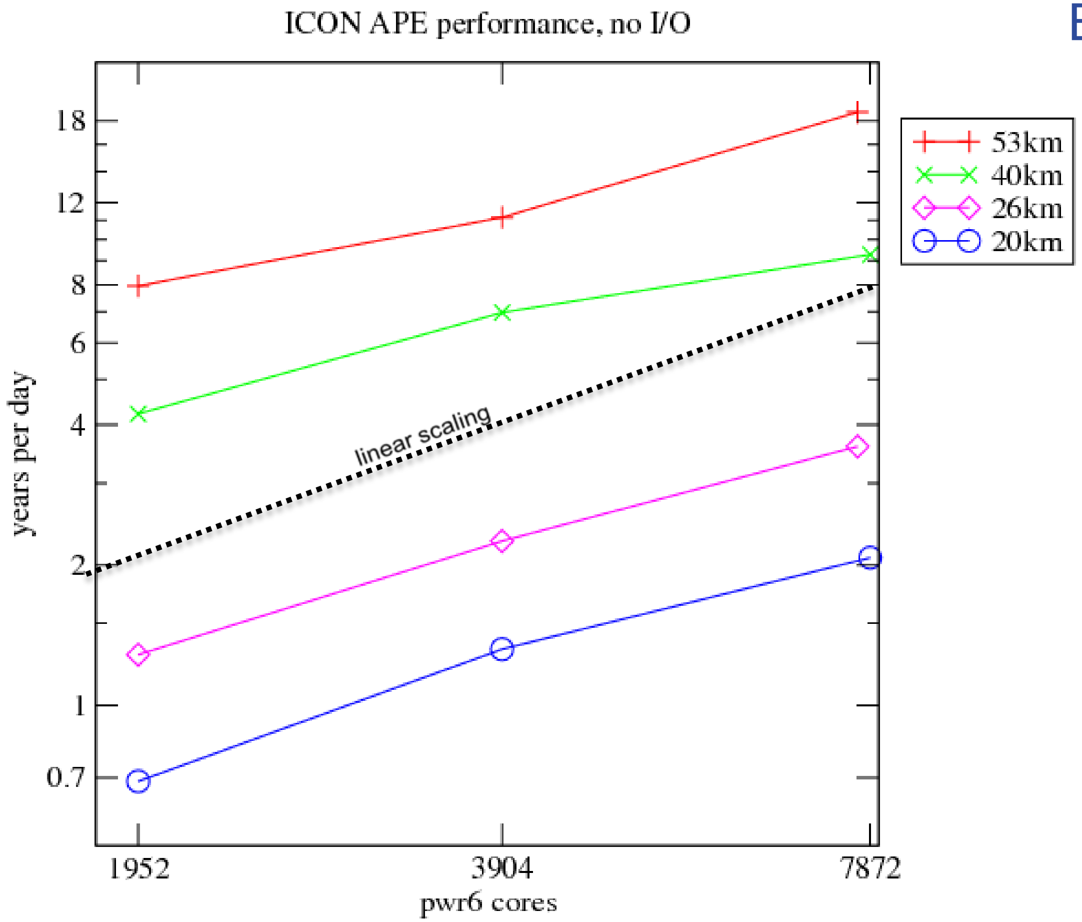
Average over 30 1-day ICON (80 km mesh size) forecasts compared to IFS analyses, July 2012







Computational performance and scaling



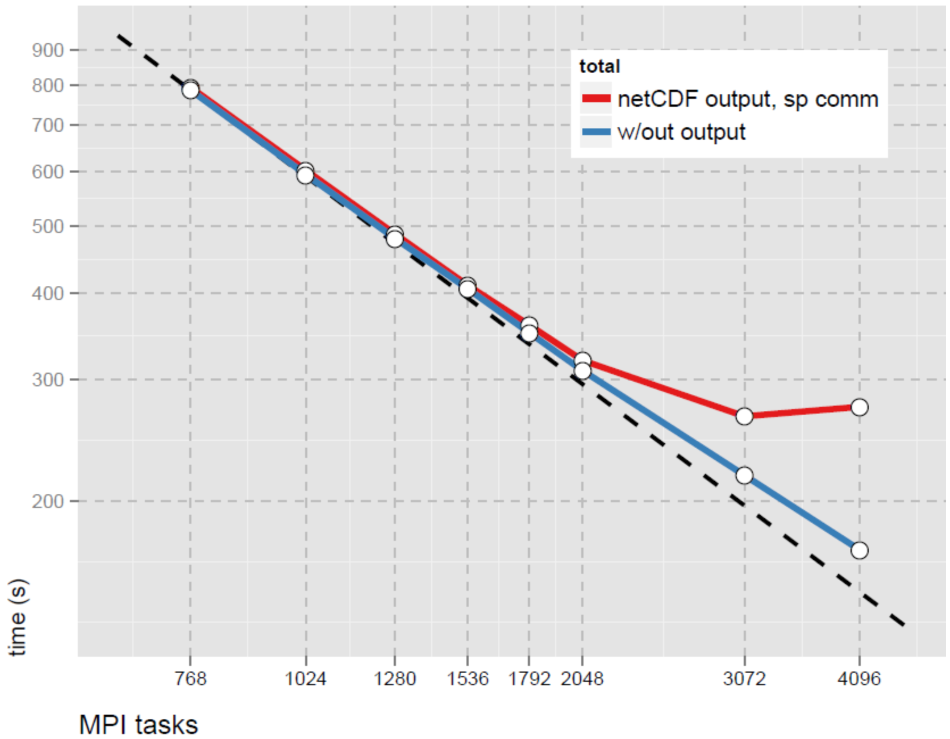
Benchmark preparation test on IBM pwr6 @ DKRZ/Hamburg

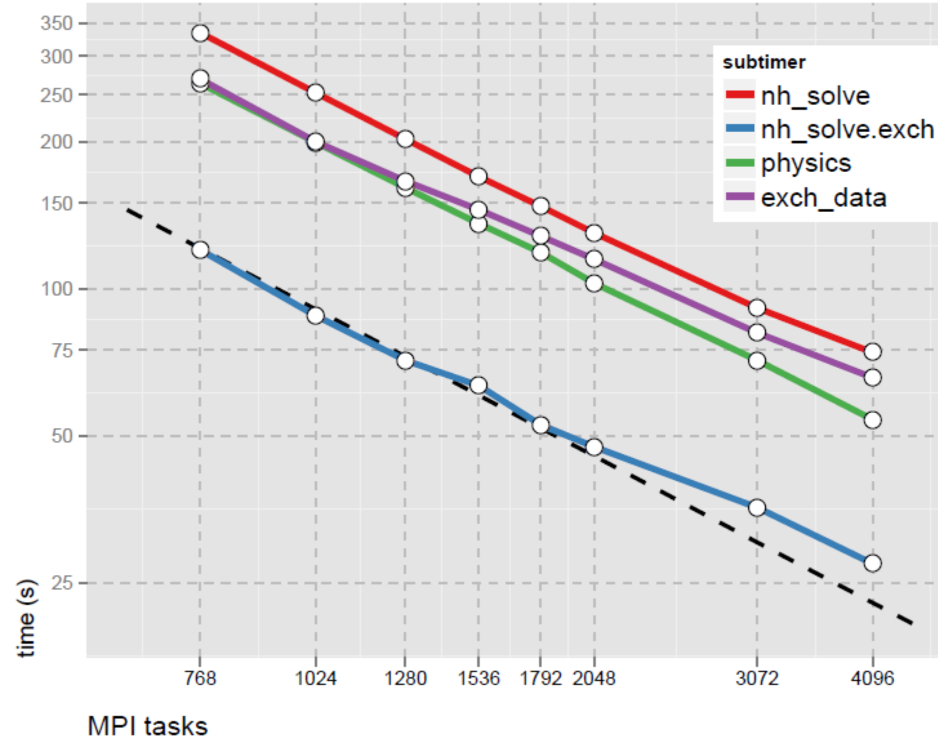
Setup:

Aqua-planet experiment with full physics coupling except land-surface model, 96 model levels, horizontal mesh sizes 53 km – 20 km, result without output

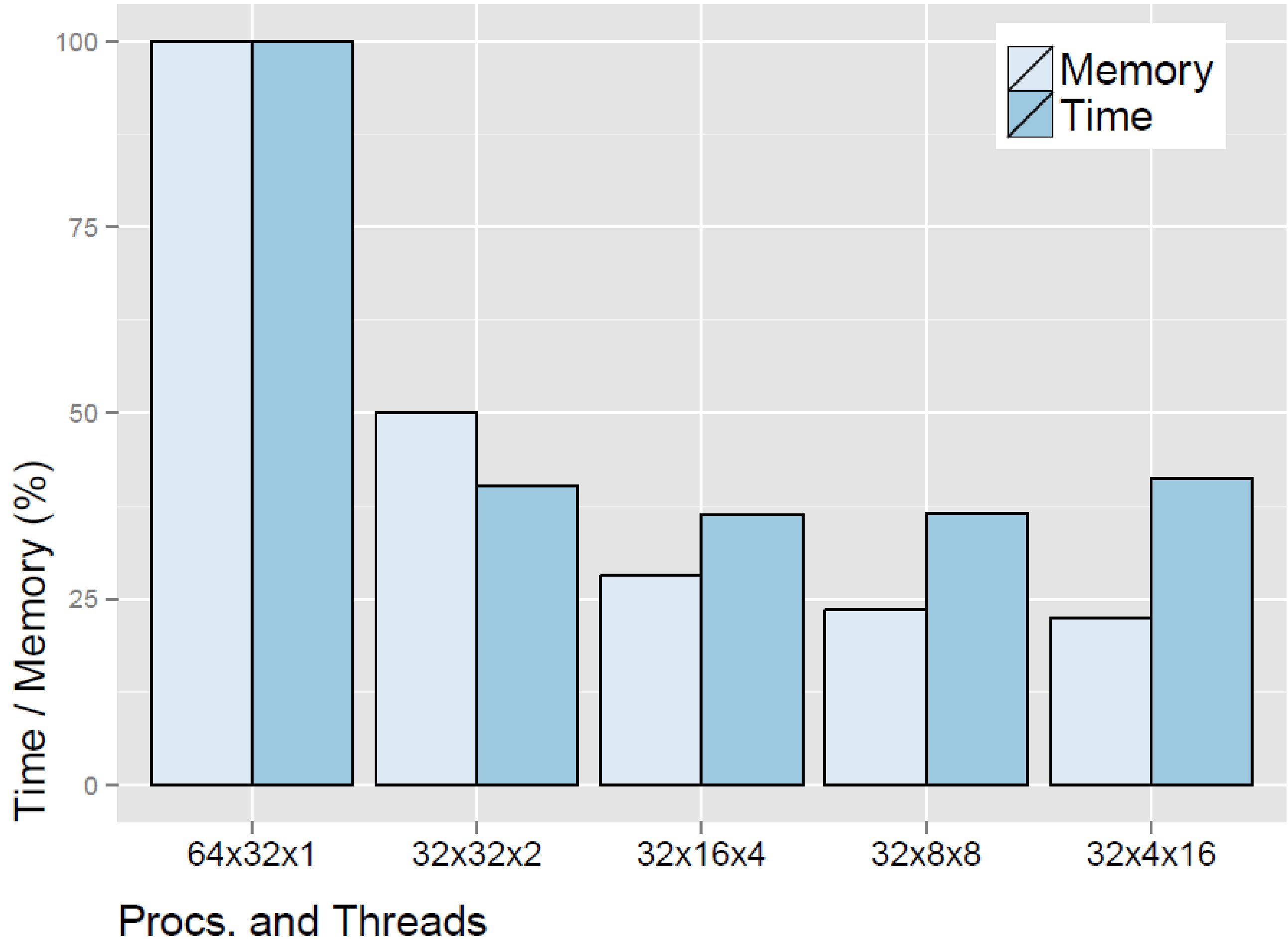
ICON RAPS 2.0 benchmark test on IBM pwr7 @ ECMWF

Complex multiply nested setup with 20/10/5 km mesh size, 90/60/54 levels, real-case setup with interpolated IFS analysis data and full physics coupling, timings refer to 8-hour forecast





Sensitivity study: dependence of runtime and maximum memory allocation on the number of OpenMP threads (with SMT); IBM pwr7 @ ECMWF



Summary: strengths and weaknesses of ICON

- The dynamical core of ICON combines efficiency, high numerical stability and improved conservation properties and has been tested for a scale range of three orders of magnitude
- The two-way nesting offers high flexibility, supports vertical nesting and a limited-area mode, and induces very weak artifacts
- Memory scaling and I/O still need performance improvements
- The forecast quality in stand-alone mode is already substantially better than for GME, but there are still some weaknesses and biases, e.g. in the moisture field
- Tests with own data assimilation have only recently started due to difficulties with GRIB2 encoding and the need of extensions of the GRIB-API; a lot of tuning will have to be done during the subsequent months

Time schedule towards operational use

- **Ongoing: extensive test series with interpolated IFS analysis to optimize forecast quality of ICON**
- **Ongoing: preparatory tests with 3DVar data assimilation to detect and solve quality problems and to tune the coupled system**
- **Q4/2013: Start of preoperational test suite and extensive sensitivity experiment series**
- **Q4/2014: First step of operational use of ICON: replacement of GME by global-only ICON with 13 km mesh size**
- **Q3/2014 or Q4/2014: First official public release of ICON**
- **Q2/2015: Second step of operational use of ICON: activation of 6.5 km nested domain in order to replace COSMO-EU**