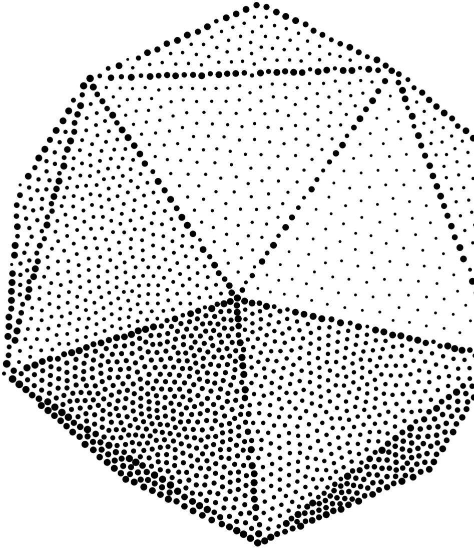
ICON Stock-Taking Report

Florian Prill, Günther Zängl, and the ICON Team

COSMO GM 2013
September 2–5, 2013

Outline

- Introduction: Main goals of the ICON project
- Important features of ICON
- Technical model characteristics
- Selected results and ongoing work
- Schedule towards operational application



Introduction

ICON = ICOsahedral Nonhydrostatic Model

Joint development project of DWD and Max-Planck-Institute for Meteorology for the next-generation global NWP and climate modelling system

- **Nonhydrostatic dynamical core** on an icosahedral-triangular C-grid; coupled with full set of physics parameterizations
- **Two-way nesting** with capability for multiple non-overlapping nests per nesting level; vertical nesting, one-way nesting mode and limited-area mode are also available

Primary Development Goals

- Applicability on a wide range of scales in space and time down to mesh sizes that require a nonhydrostatic dynamical core
- Better conservation properties (air mass, mass of trace gases and moisture, consistent transport of tracers)
- Built to run on vector computers as well as x86 based commodity clusters, scales to $\mathcal{O}\left(10^4+\right)$ cores
- 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
- At MPI-M: ocean model based on ICON grid structures and operators; limited-area mode of ICON to replace regional climate model REMO

Dissemination and Exchange

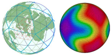
Models:

COSMO
common physics packages

ICON-ART
aerosols and reactive trace gases

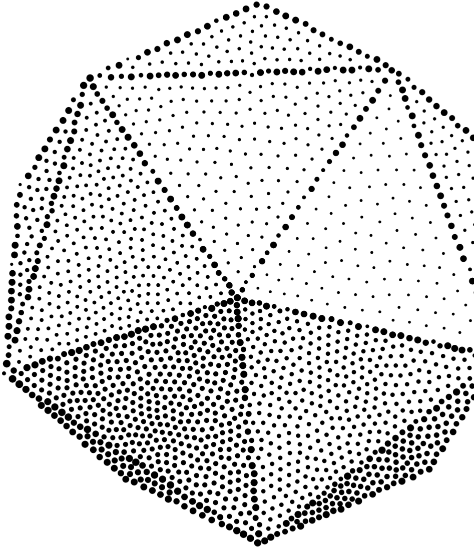
Projects:

HD(CP)^2
very high-resolution simulation
to advance the parameterization of clouds and precipitation



ICOMEX
ICOsahedral-grid Models for EXascale Earth system simulations

Model Description



Nonhydrostatic Equation System (Dry Adiabatic)

$$
\begin{aligned}
\partial_t v_n \quad &+ (\zeta + f)\, v_t \quad + \partial_n K + w\,\partial_z v_n &=& \; -c_{pd}\theta_v \partial_n \pi \\
\partial_t w \quad &+ \mathbf{v}_n \cdot \nabla w \quad + w\,\partial_z w &=& \; -c_{pd}\theta_v \partial_z \pi - g \\
\partial_t \rho \quad &+ \nabla \cdot (\mathbf{v}\rho) = 0 && \\
\partial_t (\rho\theta_v) &+ \nabla \cdot (\mathbf{v}\rho\theta_v) = 0 &&
\end{aligned}
$$

(v_n, w, ρ, θ_v: prognostic variables)

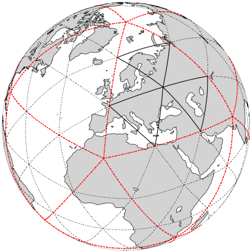
- v_n, w: velocity components
- ρ: density
- θ_v: virtual potential temperature
- K: horizontal kinetic energy
- ζ: vertical vorticity component
- π: Exner function

Discretization

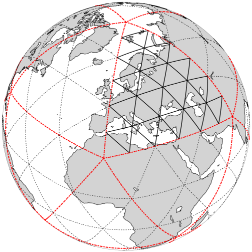
- Arakawa C-grid with mass-related quantities at *cell circumcenters*
- Lorenz-type vertical staggering
- reference atmosphere: only used internally

The Horizontal Grid

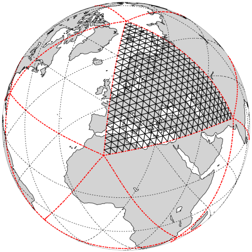
Spherical geodesic grids derived from the icosahedron



R3B00



R3B01



R3B03 optimized

Grid Structure with Nested Domains

- grid topology stored in NetCDF file format (GRIB format infeasible)
- Effective mesh size: $\Delta x \approx 5050/(\,\underset{\text{root divisions}}{n}\;2^{\underset{\text{bisections}}{k}}\,)$ [km]

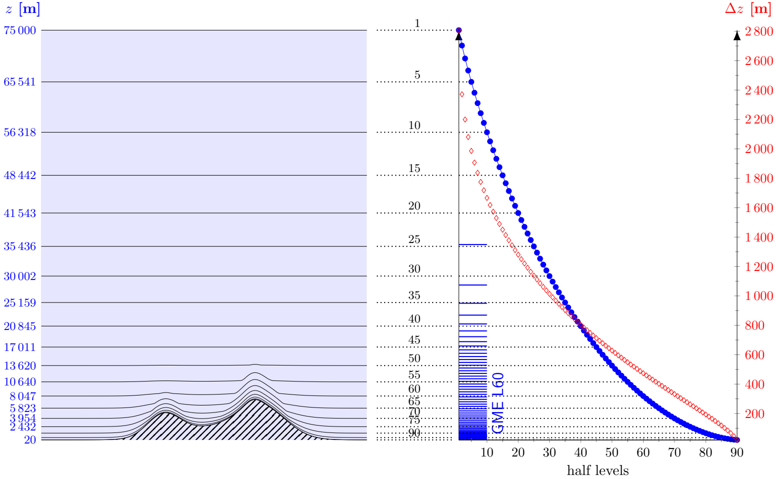
Example:

R2B7 : $n = 2, k = 7$

20 km global res.
$\approx 1.3 \cdot 10^6$ spherical triangles

$\times\, 90$ vertical levels (up to 75 km)

Smooth Level Vertical (SLEVE) Coordinate



Numerical Implementation

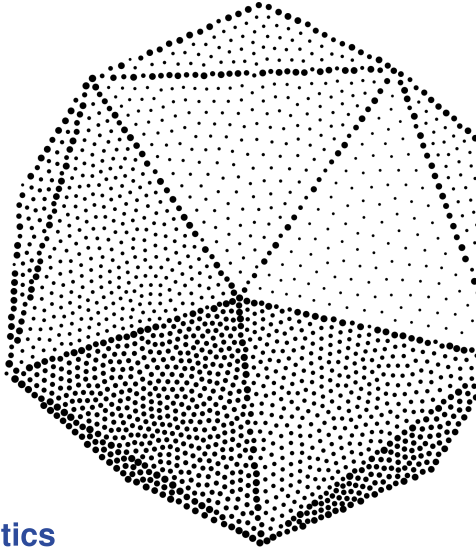
- Two-time-level predictor-corrector time stepping scheme
- Horizontally explicit, vertically implicit on sound waves;
  larger time step (usually 4x or 5x) for tracer advection/fast physics
- Finite-volume tracer advection scheme (Miura) with 2nd-order and 3rd-order accuracy for horizontal tracer advection
- 2nd-order 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
- Mahrer-type pressure discretization (Zängl 2012, MWR)

Physics Parameterizations

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
	Louis (1979)	1^{st} order closure	GME
	Neggers, Köhler, Beljaars (2010)	EDMF-DUALM	IFS
Land	Heise and Schrodin (2002), Machulskaya, Helmert, Mironov (2008, lake)	tiled TERRA + FLAKE + multi-layer snow	GME/COSMO
	Raddatz, Knorr	JSBACH	ECHAM6

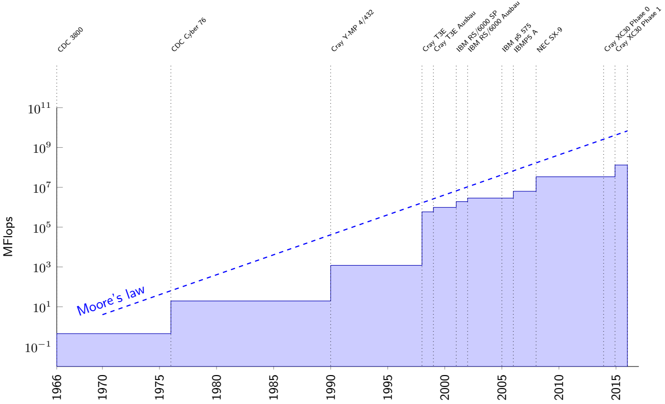
Physics-Dynamics Coupling

- Fast-physics processes: incremental update in the sequence saturation adjustment → transfer scheme → surface coupling → 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



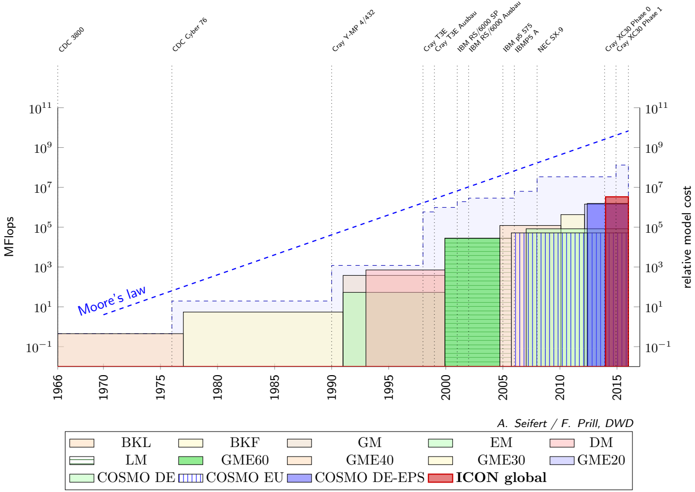
Technical Model Characteristics

Growth of Performance and Model Cost at DWD



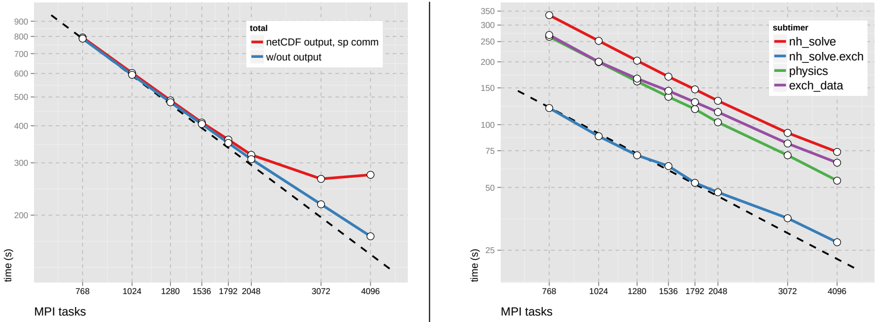
A. Seifert / F. Prill, DWD

Growth of Performance and Model Cost at DWD



A. Seifert / F. Prill, DWD

Flat-MPI Performance



Test setup: **ICON RAPS 2.0**, **IBM Power7**
20/10/5 km, 8 h forecast, reduced radiation grid

(S. Körner, DWD, 03/2013)

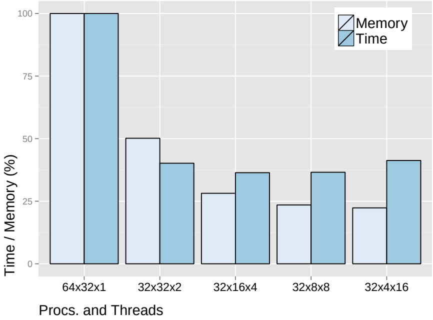
Hybrid Performance

Multicore transition:

75% of Top500 HPC systems have ≥ 6 cores per socket.

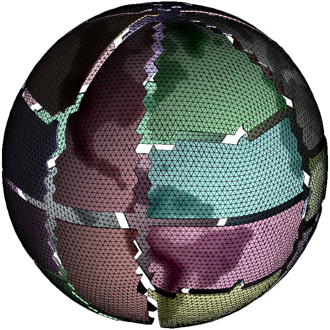
On-chip clock rates have increased only moderately.

The ICON model supports hybrid parallelization with MPI + OpenMP



Test setup: **ICON RAPS 2.0**, **IBM Power7**
20/10/5 km, 1000 steps

ICON's Domain Decomposition



Geometric decomposition, 20 partitions

Criteria:

1. **Static load balancing**, e. g. every PE comprises sunlit and shadowed parts of the globe
2. **Communication reduction**

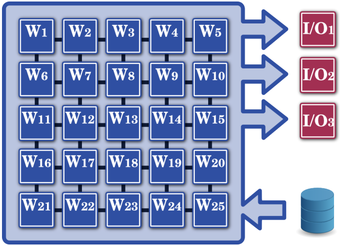
Explicit array partitioning with

- halo regions
- lateral boundary regions
- interior points

. . . avoids conditionals in iterations.

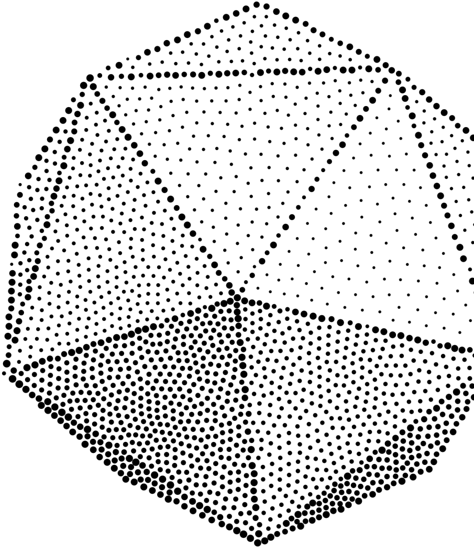
I/O: Bottleneck for High-Resolution NWP

Classical root I/O of high-resolution data becomes a critical issue.



The ICON model offloads all computed results to dedicated output nodes.

- computation and I/O overlap
- fast system layer: *Climate Data Interface*
- WMO GRIB2 standard (ECMWF's `GRIB_API`)



Current State of Affairs

Selected Experiments and Results

(A) Idealized test

Determine ICON's overall order of convergence

(B) Selected results of NWP test suite

WMO standard verification, comparison to GME

(C) Ongoing work: coupling with data assimilation

Idealized Test

Baldauf, Reinert and Zängl demonstrated that a rigorous assessment of ICON's model accuracy is possible (QJRMS, 2013, in rev.).

3D non-hydrostatic Euler equations on the sphere:

$$\begin{aligned}
\partial_t \mathbf{v} + \mathbf{v} \cdot \nabla \mathbf{v} &= -\nabla p/\rho - g\,\mathbf{e}_z - 2\,\mathbf{\Omega} \times \mathbf{v} \\
\partial_t \rho + \mathbf{v} \cdot \nabla \rho &= -\rho \nabla \cdot \mathbf{v} \\
\partial_t p + \mathbf{v} \cdot \nabla p &= c_s^2 \left(\partial_t \rho + \mathbf{v} \cdot \nabla \rho\right) \qquad c_s^2 = R\,p/\rho
\end{aligned}$$

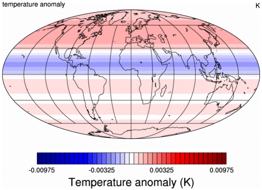
Slight simplifications (extension of DCMIP test case 3):

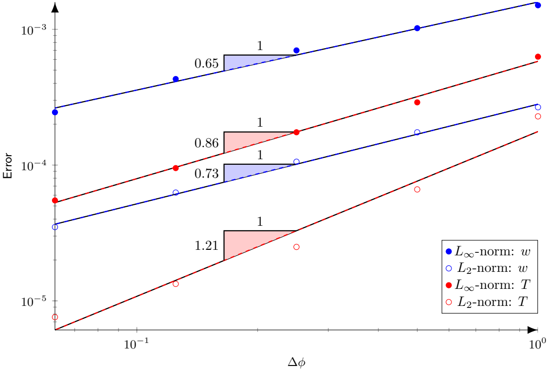
- adiabatic
- rigid lid BC's: $w\big|_{\text{surface}} = w\big|_{\text{top}} = 0$
- Coriolis term: global f-plane approximation

Test the model response to short time-scale wave motion triggered by temperature perturbation.

Convergence Order of the Model

Small earth simulation: $r_s \leftarrow r_{\text{earth}}/50$





For sufficiently fine resolutions: spatio-temporal convergence rate ≈ 1

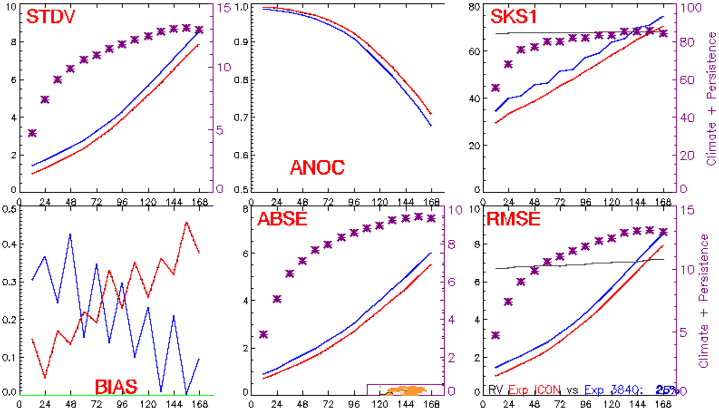
WMO Standard Verification

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 and **13 km**
  90 levels up to 75 km (no nesting)
- Reference experiment with GME40L60 with interpolated IFS data
  WMO standard verification on 1.5° regular grid

$$
\begin{array}{llll}
\mathrm{BIAS} = \overline{\mathbf{F}-\mathbf{A}} & & \mathrm{STDV} = \overline{\left[\mathbf{F}-\mathbf{A}-\overline{\mathbf{F}-\mathbf{A}}\right]^2} \\
\mathrm{ABSE} = \overline{|\mathbf{F}-\mathbf{A}|} & & \mathrm{ANOC} = \dfrac{\overline{\left[\mathbf{F}-\mathbf{R}-\overline{\mathbf{F}-\mathbf{R}}\right]\left[\mathbf{A}-\mathbf{R}-\overline{\mathbf{A}-\mathbf{R}}\right]}}{\sqrt{\overline{\left[\mathbf{F}-\mathbf{R}-\overline{\mathbf{F}-\mathbf{R}}\right]^2}\;\overline{\left[\mathbf{A}-\mathbf{R}-\overline{\mathbf{A}-\mathbf{R}}\right]^2}}} \\
\mathrm{RMSE} = \sqrt{\overline{(\mathbf{F}-\mathbf{A})^2}} & & \mathrm{SKS1} = 100\,\dfrac{\sum|\mathbf{G}_F-\mathbf{G}_A|}{\sum\max\left(|\mathbf{G}_F|,|\mathbf{G}_A|\right)}
\end{array}
$$

Verification: Sea-Level Pressure, January 2012



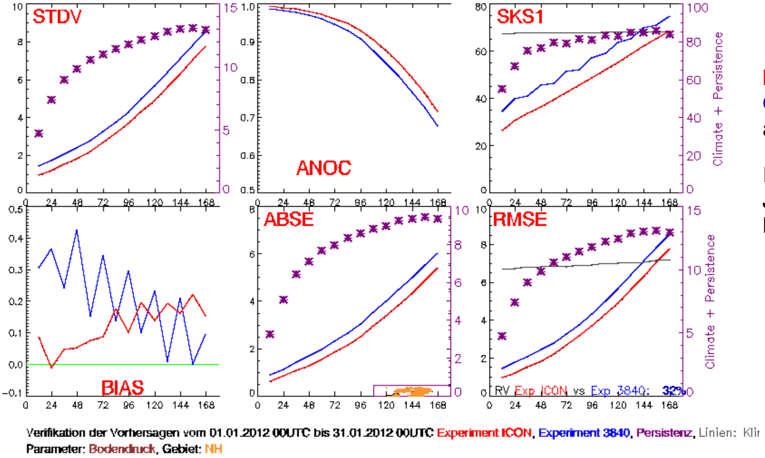
Verifikation der Vorhersagen vom 01.01.2012 00UTC bis 31.01.2012 00UTC Experiment ICON, Experiment 3840, Persistenz, Linien: Kli
Parameter: Bodendruck, Gebiet: NH

ICON
GME40
against IFS

ICON 40km
January 2012
NH

Verification: G. Zängl, U. Damrath, 08/2013 (DWD)

Verification: Sea-Level Pressure, January 2012



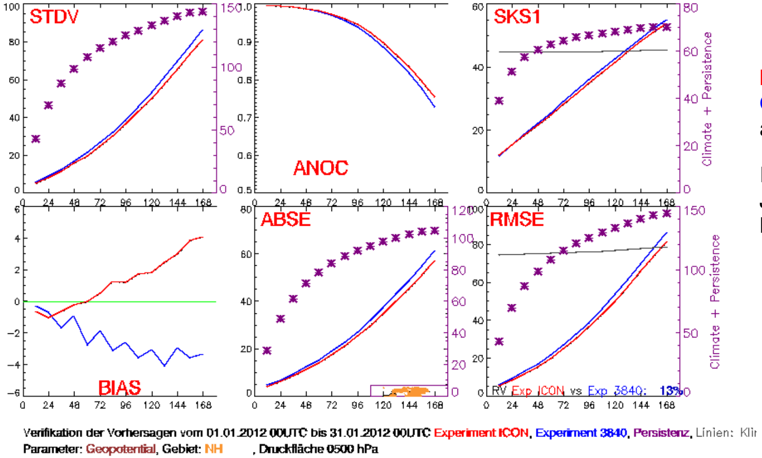
Verifikation der Vorhersagen vom 01.01.2012 00UTC bis 31.01.2012 00UTC Experiment ICON, Experiment 3840, Persistenz, Linien: Klir
Parameter: Bodendruck, Gebiet: NH

ICON
GME40
against IFS

ICON **13km**
January 2012
NH

Verification: G. Zängl, U. Damrath, 08/2013 (DWD)

Verification: Geopotential 500hPa, January 2012



Verifikation der Vorhersagen vom 01.01.2012 00UTC bis 31.01.2012 00UTC Experiment ICON, Experiment 3840, Persistenz, Linien: Klir
Parameter: Geopotential, Gebiet: NH , Druckfläche 0500 hPa

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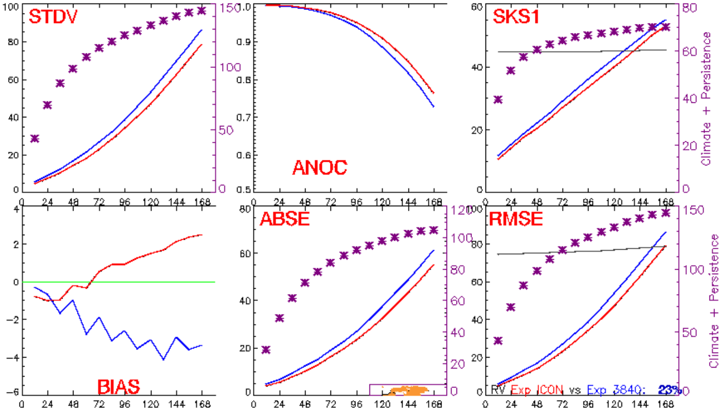

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ICON
GME40
against IFS

ICON **13km**
January 2012
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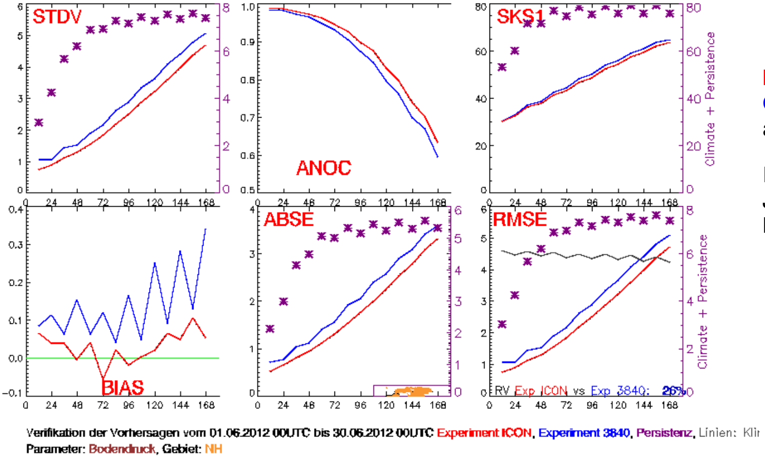
Verification: G. Zängl, U. Damrath, 08/2013 (DWD)

Verification: Sea-Level Pressure, June 2012



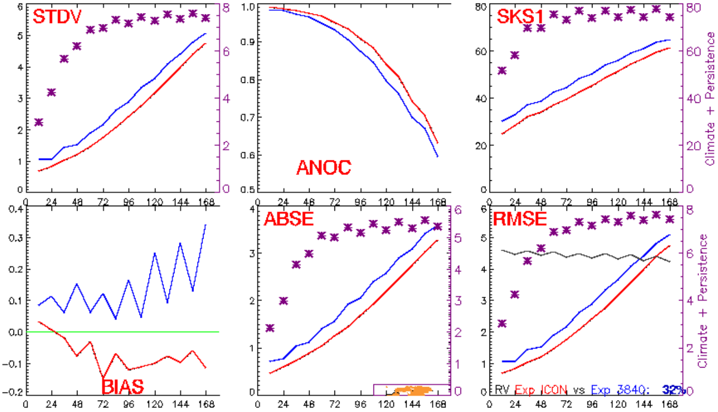
Verifikation der Vorhersagen vom 01.06.2012 00UTC bis 30.06.2012 00UTC Experiment ICON, Experiment 3840, Persistenz, Linien: Klir
Parameter: Bodendruck, Gebiet: NH

ICON
GME40
against IFS

ICON 40km
June 2012
NH

Verification: G. Zängl, U. Damrath, 08/2013 (DWD)

Verification: Sea-Level Pressure, June 2012



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ICON
GME40
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ICON **13km**
June 2012
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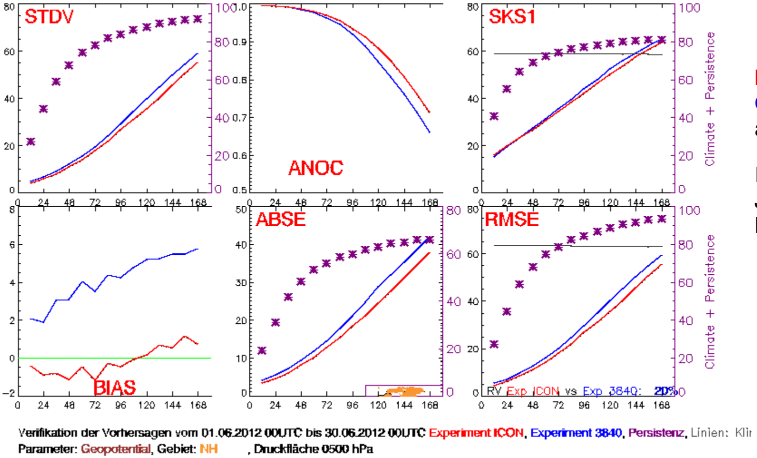

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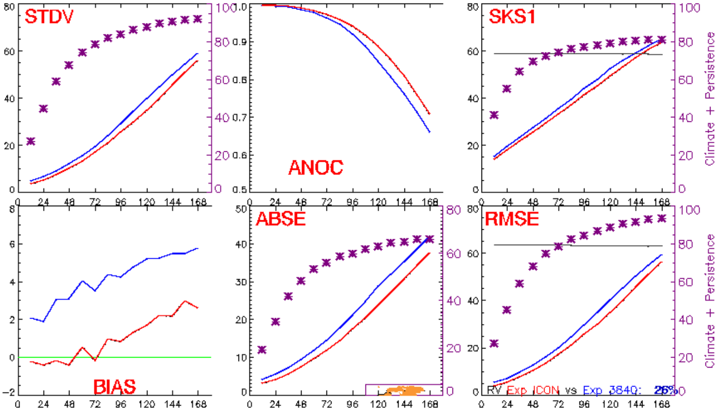

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Parameter: Geopotential, Gebiet: NH , Druckfläche 0500 hPa

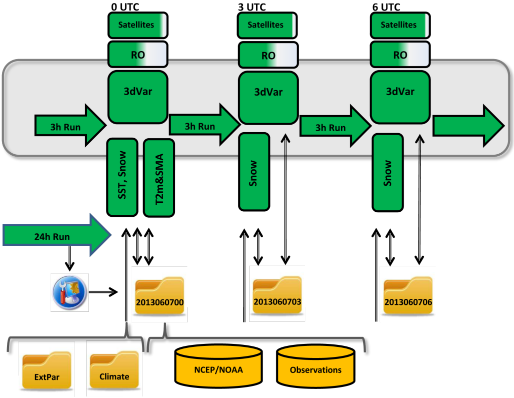
ICON
GME40
against IFS

ICON **13km**
June 2012
NH

Verification: G. Zängl, U. Damrath, 08/2013 (DWD)

Integrated System of Data Assimilation and Forecast

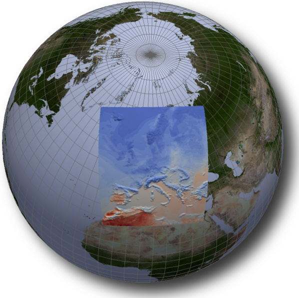
Ongoing: Systematic analysis and optimization of forecast quality of ICON using test series with continuous assimilation cycling



R. Potthast, H. Anlauf (DWD)

Limited-Area Mode

The HD(CP)^2 project will push forward the development of the limited-area version of ICON



- Capability of generating and reading time-dependent boundary data
- Upgrade the non-hydrostatic dynamical core and the physical parameterizations of ICON to the needs arising from very small scales
- Aim: Length scales down to $\Delta x = 100\,\text{m}$ over Germany for LES applications

ICON Ensemble

Short range ensemble required for EnKF (J. Ambadan, DWD).

ICON forecast ensemble: First experience within the SFP

"Erschließung und Intensivierung der Nutzung von Fernerkundungsdaten"

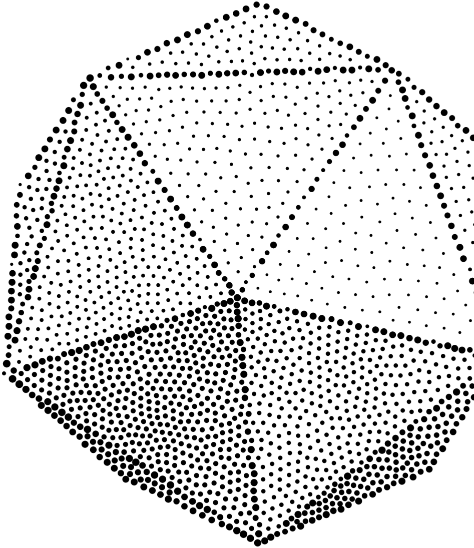
Milestones until 2012 – 2014 (M. Denhard, DWD):

- implementation of a process chain for a global ensemble forecast
- evaluation of statistical properties
- optimization for short-range weather forecasts over Europe

Tentative schedule for an operational ICON ensemble:

- roll-out plan: ca. 2017
- configuration $\sim$ 20 members, 72 hrs forecast

Also HD(CP)^2 S5.WP3: Ensemble simulations and uncertainty (D. Klocke, DWD)



Final Remarks

Final Remarks

The global ICON model is entering the home stretch

- Verification results are on par / exceeding the GME40L60
- optimization of forecast quality still ongoing
- Technical parts scale on massively parallel systems

The ICON forecast model has matured over the last 12 months, but . . .

- the model is **not yet a turnkey application software**, still code development needed!

COSMO-CLM

December 12, 2013 1:30 – 4:30 pm: DWD, Offenbach
Information event for CLM applications!

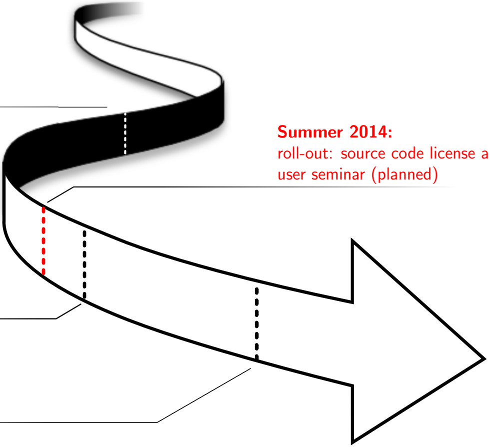
ICON Modelling Framework

- **ICON RAPS benchmark**
  for HPC vendors
- **Stand-alone grid generator**
  Public grid repository on the Web (`http://icon-downloads.zmaw.de`)
- **Pre- and post-processing utilities**
  - interpolate to/from regular grids
  - extract data sets (local regions)
  - locate cell indices

Yet to come:

- Official releases
- ICON documentation and database description
- Relaunch of public website
- User tutorials

Schedule Towards Operational Application



Q3 – Q4/2013:
start of pre-operational tests
with data assimilation

Summer 2014:
roll-out: source code license and documentation,
user seminar (planned)

Q4/2014:
first step of operational use:
replacement of GME with 13 km
ICON without nesting

Q2/2015:
replacement of COSMO-EU by
nested ICON domain (13–6.5 km)

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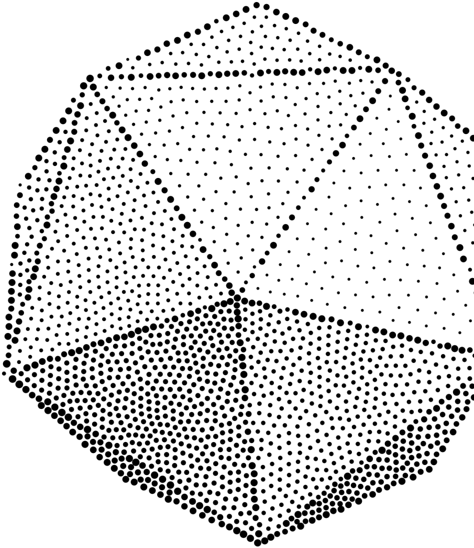
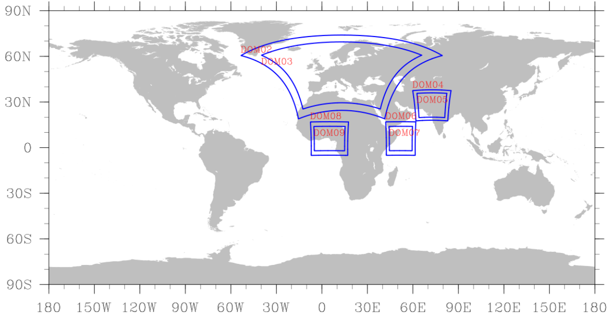
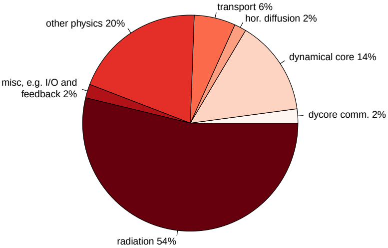


Appendix

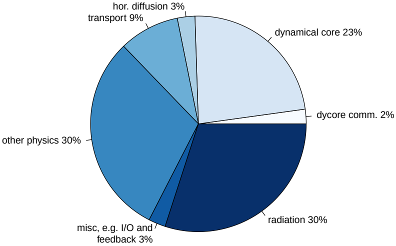
Appendix: Performance Test Case



Appendix: Effect of Reduced Radiation Grid



R2B06, without reduced radiation grid



with reduced radiation grid