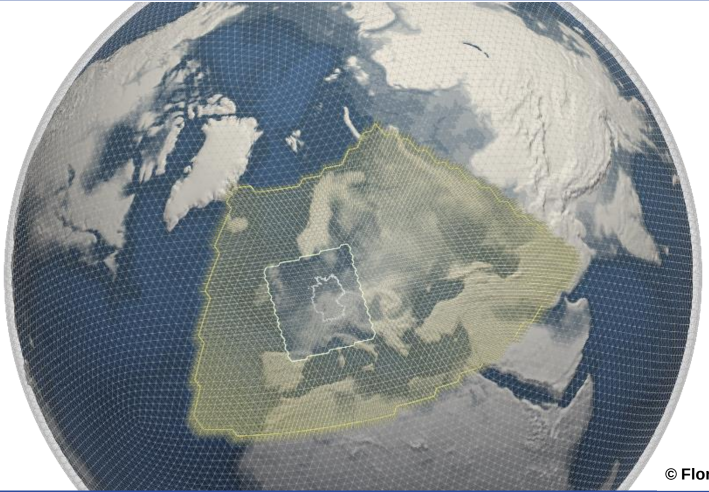


© Florian Prill, DWD

Numerical Aspects of the ICON Atmosphere Model

Daniel Reinert, Günther Zängl

Deutscher Wetterdienst, Offenbach

DWD Academic ICON Course 2025, July 21-25, Hamburg

Outline

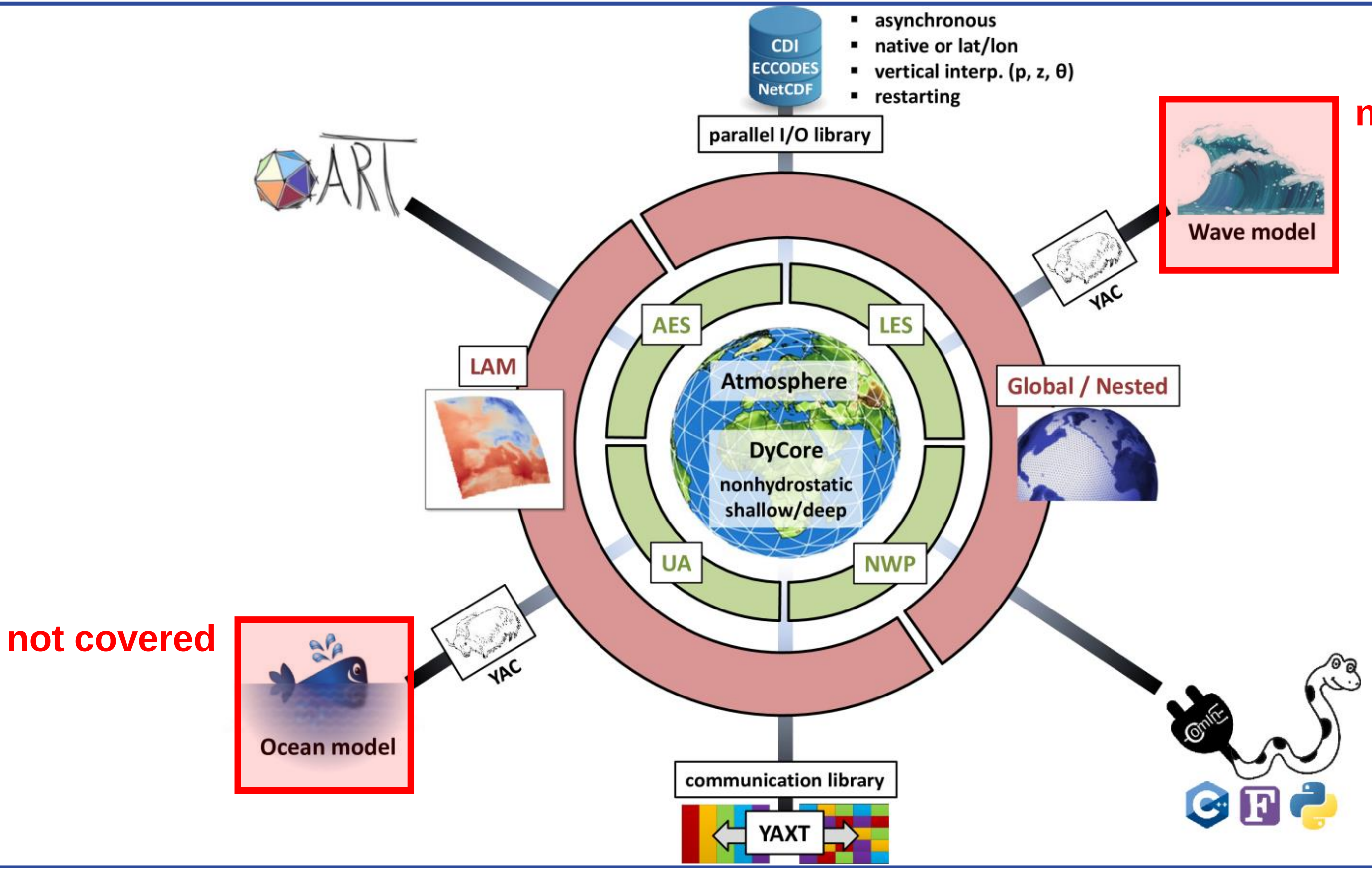
- **The ICON modelling framework**
  model components, historical review
- **Model Grid**
  horizontal and vertical grid topology
- **Governing equations and discretization aspects**
  prognostic variables, temporal and spatial discretization
- **Physics-dynamics coupling**
  coupling strategy, *NWP physics package*
- **Diffusion and Filters**
  divergence averaging, IAU, sponge layers, hyperdiffusion
- **Progress in Forecast Quality**
  past decades until today

The ICON Modelling Framework

Numerical Aspects of the ICON Atmosphere Model

ICON component models

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

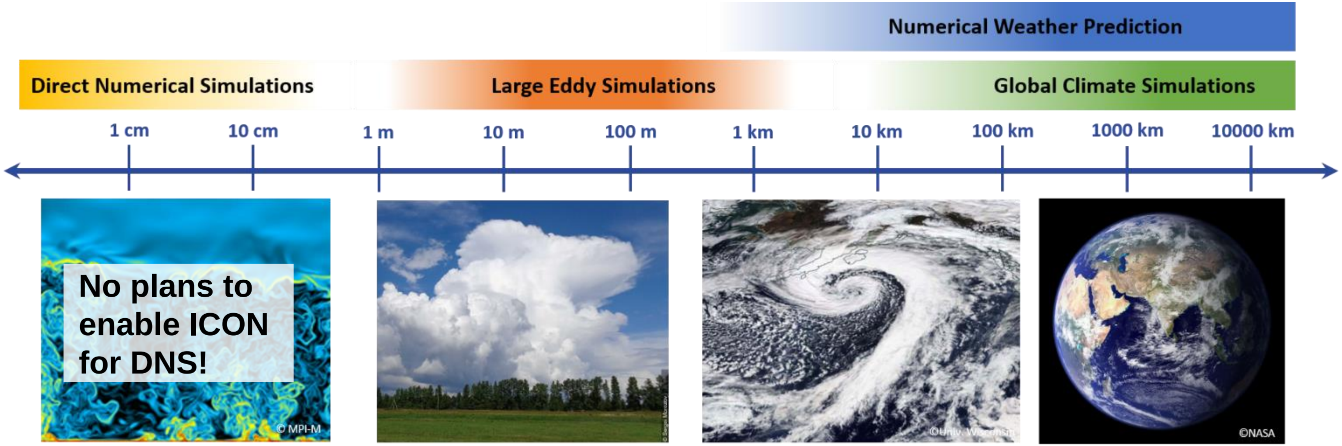


Flavors of ICON-Atmosphere

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

ICON-NWP (UA)	ICON-LES	ICON-AES	not covered
`iforcing=3`	`iforcing=3`	`iforcing=2`	

- Identical dynamical core + tracer transport
  (nonhydrostatic core is able to handle all scales)
- Differences wrt the physical parameterization suite



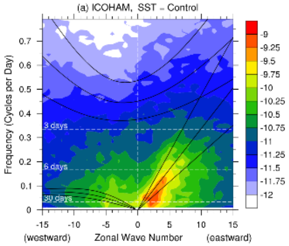
Different grid resolutions require different level of parameterization

A brief historical account of ICON (NWP)

2001 Decision about **cooperation between DWD und MPI-M** for a joint development of a **new global modelling system** for NWP and climate

2004 First project positions; development of a **shallow-water model** based on the ICON grid structure

2008 **Hydrostatic dynamical core** with numerics partly imported from ECHAM, start of implementation of tracer transport schemes.



2010 **Nonhydrostatic dynamical core,** coupling with physics parameterizations.

2011 First real-data tests

2012 First **comparison** of forecast skills **against GME** based on IFS analyses (encompassed by extensive test series in order to optimize forecast quality)

A brief historical account of ICON (NWP)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

2012 **Coupling to 3D-Var** data assimilation scheme. Further experiments to optimize forecast quality.

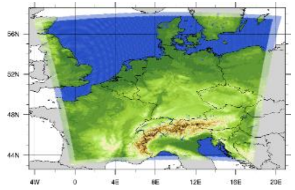
08 / 2014 Start of preoperational phase

01 / 2015 **Start of operational production at DWD** (13 km, 90 levels up to 75 km)

06 / 2015 Activation of **nested domain over Europe** (6.5 km, 60 levels up to 22.5 km)

01 / 2016 **Ensemble data assimilation system** (Localized Ensemble Transform Kalman Filter, 40 members)

02 / 2021 Start of operational production for regional mode **ICON-D2** (2.2 km, 60 levels up to 22.5 km, 40 members)

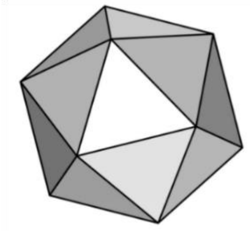


07 / 2024 operational rapid update cycle **ICON-D2-RUC**

Model Grid

Numerical Aspects of the ICON Atmosphere Model

Horizontal grid topology

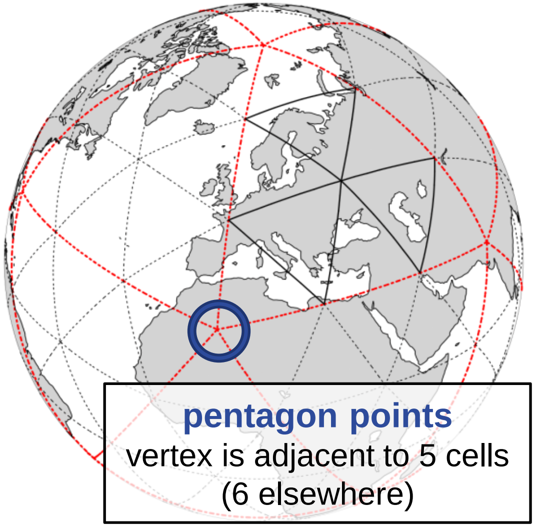


- grid generation is based on the Icosahedron
- By **R**n**B**k we denote a grid that originates from an icosahedron whose
  - edges have been initially divided into n parts,
  - followed by k subsequent edge bisections.
  - grid optimized by 'spring dynamics' step
- The total number of grid cells in the ICON grid is given by

$$n_{\text{cells}} = 20\, n^2 4^k$$

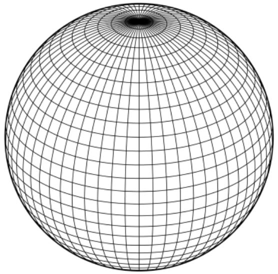
- Operationally used at DWD:

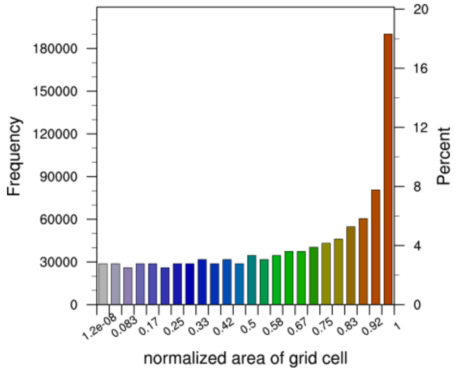
$$\text{R3B7} \approx 2.95\,\text{million cells}$$



Comparison to regular lat-lon

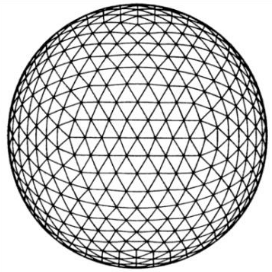
Lat-lon grid

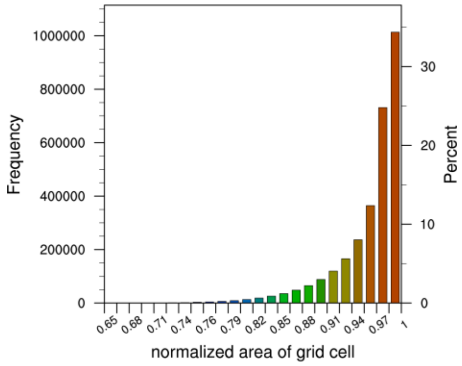




- ➢ Highly non-uniform tessellation, leading to well known ‚**pole-problem**‘.

Icosahedral grid



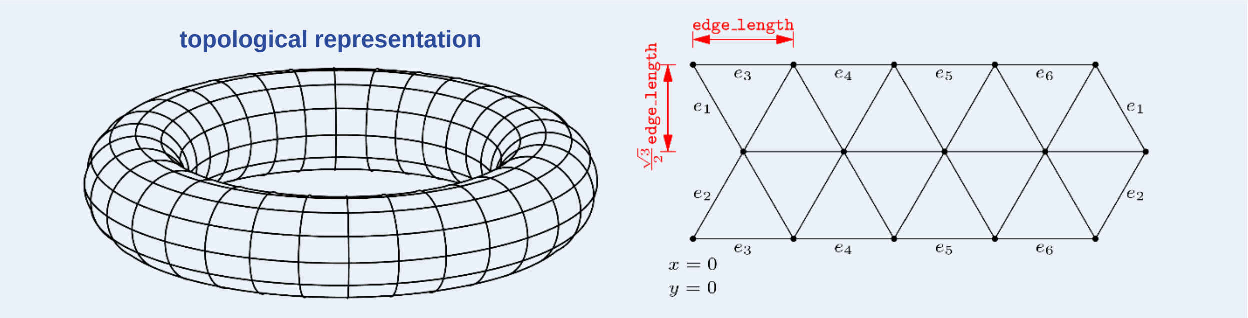


- ➢ Quasi-uniform tessellation of the sphere. (not perfect, though)

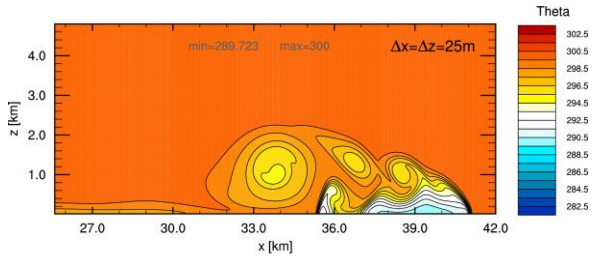
$$\frac{\Delta A_{largest}}{\Delta A_{smallest}} \approx 1.55$$ **(R3B7)**

Planar torus grid

- It is possible to run ICON on a **planar torus grid**
- Equilateral planar triangles, doubly-periodic



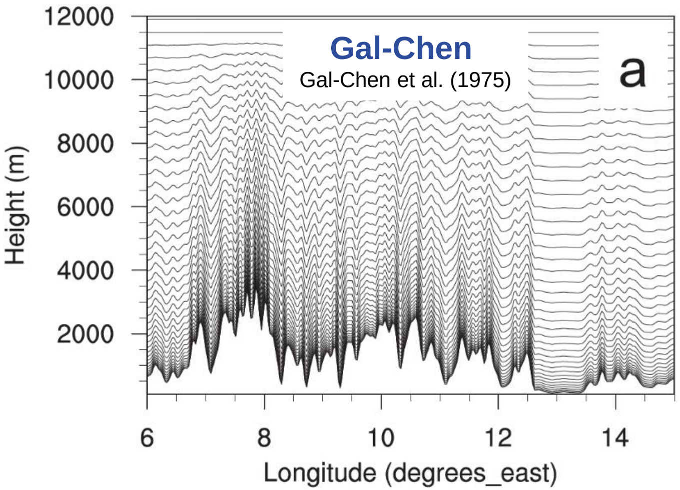
- Useful for
  - idealized LES applications (e.g. convective/neutral/stable PBL)
  - quasi 2D (x-z) idealized simulations (e.g. “Straka” test)



“Straka” density current test

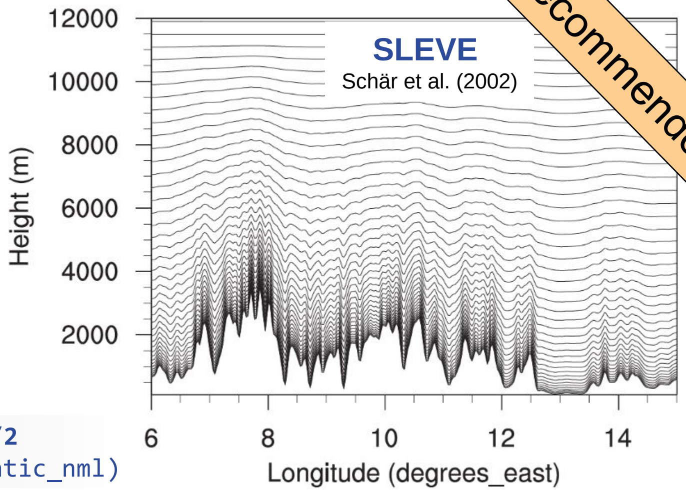
Requires special version of the grid generator.
Please contact Leonidas Linardakis, MPI-M

- **Terrain following, time constant, hybrid σ-z coordinates** (i.e. height based !)
- Level ordering: top-down
- Constructed during setup phase on the basis of namelist settings (**`sleve_nml`**)
  i.e. no input fields required



`ivctype = 1/2`
`(nonhydrostatic_nml)`

recommended

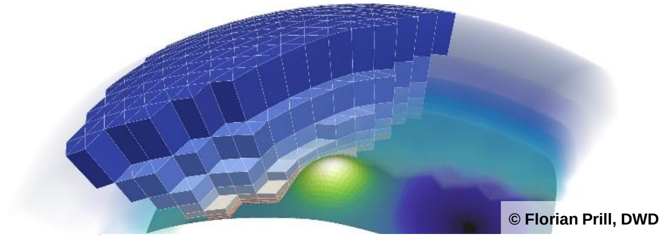


terrain features decay linearly with height

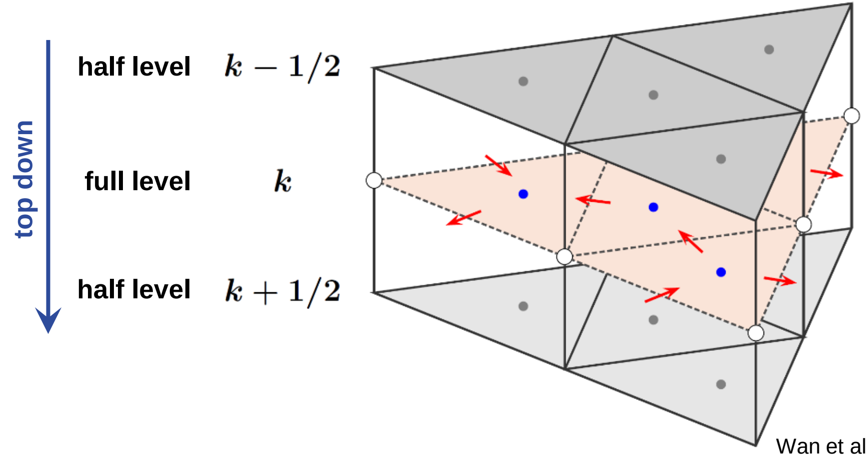
more rapid decay of small scale features

Prognostic variables and staggering

- Arakawa C-staggering in the horizontal
- Lorenz-type staggering in the vertical
- Top-down numbering



3D grid: prismatic cells



Wan et al (2013)

- v_n edge-normal vel. component
- w vertical velocity
- ρ total air density (incl. condensates)
- θ_v virtual pot. temperature
- q_i mass fractions (water vapor, rain, dust, …)

Governing Equations and Discretization Aspects

Numerical Aspects of the ICON Atmosphere Model

Full set of governing equations

- Navier-Stokes fully compressible, Hesselberg averaged, rotating reference frame
  - spherical geoid
  - shallow atmosphere (optional: deep atmosphere)
- vector invariant form $(\boldsymbol{u} \cdot \nabla \boldsymbol{u} = \nabla K + \boldsymbol{\zeta} \times \boldsymbol{u})$

momentum

$$\frac{\partial \widehat{v}_n}{\partial t} + \frac{\partial \widehat{K}_h}{\partial n} + (\widehat{\zeta} + f)\widehat{v}_t + \widehat{w}\frac{\partial \widehat{v}_n}{\partial z} = -c_{pd}\widehat{\theta}_v \frac{\partial \overline{\pi}}{\partial n} - F(v_n)$$

$$\frac{\partial \widehat{w}}{\partial t} + \widehat{\boldsymbol{v}}_h \cdot \nabla \widehat{w} + \widehat{w}\frac{\partial \widehat{w}}{\partial z} = -c_{pd}\widehat{\theta}_v \frac{\partial \overline{\pi}}{\partial z} - g$$

energy

$$\frac{\partial \overline{\rho}\widehat{\theta}_v}{\partial t} + \nabla \cdot (\overline{\rho}\widehat{\boldsymbol{v}}\widehat{\theta}_v) = \overline{Q}$$

total mass

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

partial mass

$$\frac{\partial \overline{\rho}\hat{q}_k}{\partial t} + \nabla \cdot (\overline{\rho}\widehat{q}_k\widehat{\boldsymbol{v}}) = -\nabla \cdot \left(\overline{\boldsymbol{J}}_k + \overline{\rho q_k'' \boldsymbol{v}''}\right)$$

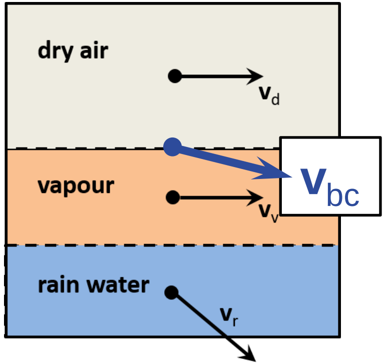
prognostic

Tutorial
Sec 3.1

Barycentric reference frame

- Equation set describes two-component (dry air + water) multiphase flow
  → derivation requires choice of a reference velocity
- Formulated in a **barycentric reference frame** (Wacker et. al, 2003)
  → reference frame impacts the specific form of the equation set
- Reference velocity (prognostic!) is the **barycentric velocity** rather than the dry air velocity

$$\boldsymbol{v}_{bc} = \frac{\sum_k \rho_k \boldsymbol{v}_k}{\sum_k \rho_k}$$



System of
dry air + vapour + condensates

Current implementation of the barycentric system uses an **approximate lower boundary condition**,
i.e. $w_{bc} = 0$ at the surface

"Dynamical core" versus "Physics"

Dynamical core: the resolved fluid component of the model
((non)-linear transport terms, pressure gradient, numerical filters)

Physics: sub-grid scale processes
(microphysics, radiation, turbulence …)

Numerical filters and diffusion

$$\frac{\partial \widehat{v}_n}{\partial t} + \frac{\partial \widehat{K}_h}{\partial n} + (\widehat{\zeta} + f)\widehat{v}_t + \widehat{w}\frac{\partial \widehat{v}_n}{\partial z} + c_{pd}\widehat{\theta}_v \frac{\partial \pi'}{\partial n} + F_{v_n} = -\frac{1}{\overline{\rho}}\left(\nabla_h \cdot \overline{\rho \boldsymbol{v}'' \boldsymbol{v}''}\right) \cdot \boldsymbol{e}_n$$

$$\frac{\partial \widehat{w}}{\partial t} + \widehat{\boldsymbol{v}}_h \cdot \nabla \widehat{w} + \widehat{w}\frac{\partial \widehat{w}}{\partial z} + c_{pd}\left(\widehat{\theta}_v \frac{\partial \pi'}{\partial z} + \theta_v' \frac{d\pi_0}{dz}\right) + F_w = -\frac{1}{\overline{\rho}}\frac{\partial}{\partial z}\overline{\rho \boldsymbol{v}'' \boldsymbol{v}''}$$

$$\frac{c_{vd} c_{pd}}{R_d}\overline{\rho}\widehat{\theta}_v \frac{\partial \overline{\pi}}{\partial t} + c_{pd}\overline{\pi}\,\nabla \cdot (\overline{\rho}\widehat{\boldsymbol{v}}\widehat{\theta}_v) - c_{pd}\overline{\pi}\,\overline{\rho}\widehat{\theta}_v \chi \nabla \cdot \widehat{\boldsymbol{v}} + F_\pi = c_{pd}\overline{\pi}\,\overline{\rho Q}$$

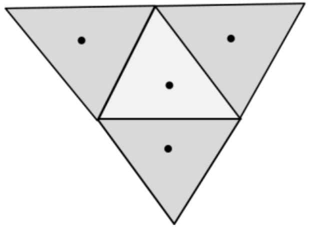
$$\frac{\partial \overline{\rho}}{\partial t} + \nabla \cdot (\overline{\rho}\widehat{\boldsymbol{v}}) = 0$$

$$\frac{\partial \overline{\rho}\widehat{q}_k}{\partial t} + \nabla \cdot (\overline{\rho}\widehat{q}_k \widehat{\boldsymbol{v}}) = -\nabla \cdot \left(\overline{J_k^z}\boldsymbol{k} + \overline{\rho q_k'' \boldsymbol{v}''}\right) + \overline{\sigma}_k$$

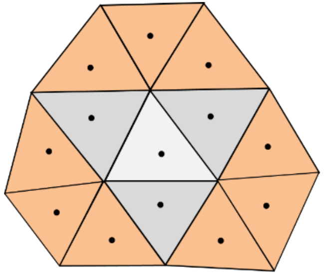
Numerical discretization: general remarks

Focus on computational speed/scalability rather than ultra high convergence rates

- **Avoidance of implicit methods**
  no global communication
- **Fully explicit time integration scheme**
  Exception: terms describing vertical sound wave propagation
- **Mixture of finite volume/finite difference discretization methods**
  mostly of 2^{nd} order in space and time
- **Local methods with small stencils**
  only direct neighbors and vertex-neighbors



3-point stencil



12-point stencil

For details see Zängl et al. (2015)

The time integration scheme in a nutshell

- **Explicit** two-time-level **predictor-corrector** time stepping **scheme** for v_n, w, ρ, π
- All terms integrated at the acoustic time step (not split-explicit)
- Exception: **implicit treatment** of terms describing **vertical sound wave** propagation (w_z, π_z). Involves solution of linear tridiagonal system for w in the vertical column.

Predictor-Corrector basic principle

Let

$$\frac{\partial \phi}{\partial t} = F(\phi, t)\,, \quad \text{with } \phi \in v_n, w, \rho, \pi$$

predictor

$$\phi^{(n+1)*} = \phi^n + \Delta t F(\phi^n)$$

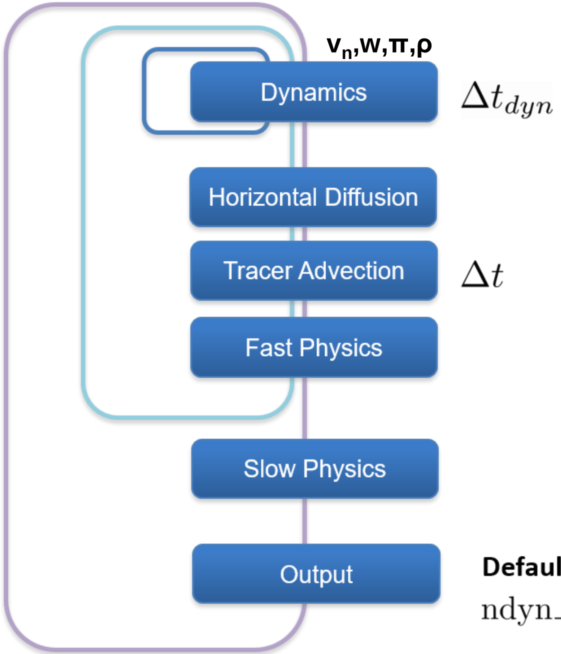
corrector

$$\phi^{n+1} = \phi^n + \Delta t \left(\alpha\, F(\phi^n) + \beta\, F(\phi^{(n+1)*})\right)\;; \quad \alpha + \beta = 1$$

ICON Tutorial Sec 3.5

Time-splitting

- Time-splitting between the dynamical core and tracer advection/physics
- Dynamical core is sub-cycled wrt. tracer advection and physics



Default:

$$\text{ndyn\_substeps} = \frac{\Delta t}{\Delta t_{dyn}} = 5$$

Setting the time step

`dtime (run_nml)`

sets Δt (not Δt_{dyn})

Example: R3B7 (13km)

$\Delta t \approx 120\text{s}$

$\Delta t_{dyn} \approx 24\text{s}$

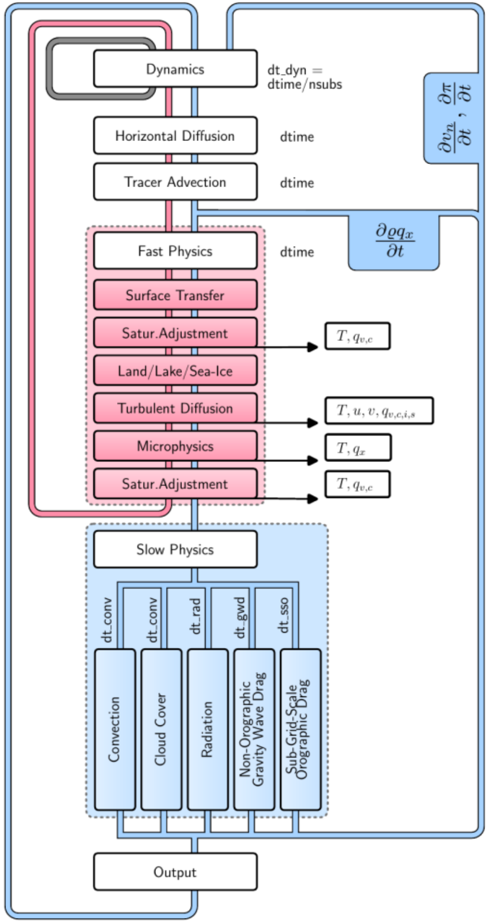
Tutorial
Sec 3.7.1

Physics-Dynamics Coupling

Numerical Aspects of the ICON Atmosphere Model

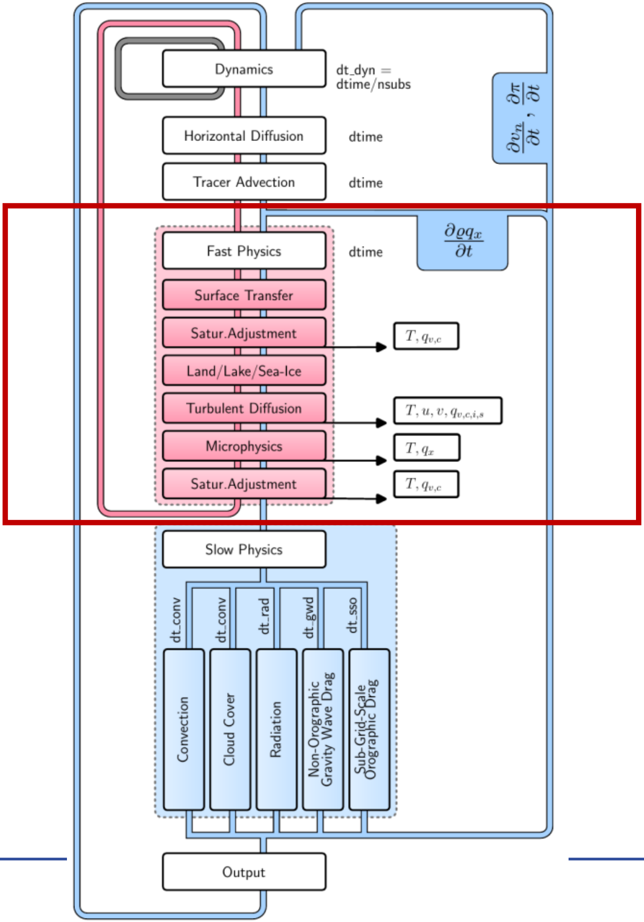
Physics-Dynamics coupling

- We distinguish between “fast physics” and “slow physics”
- On the basis of process time scales versus model time step
- Processes are treated isochorically (ρ=const, not p!)



Physics-Dynamics coupling

- We distinguish between “fast physics” and “slow physics”
- On the basis of process time scales versus model time step
- Processes are treated isochorically (ρ=const, not p!)



Fast physics

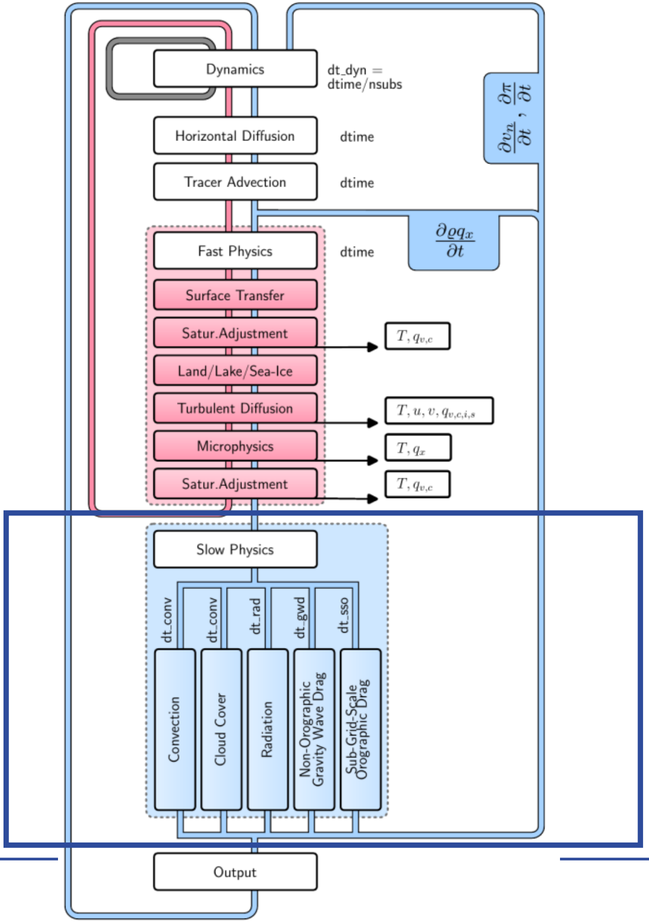
- called every advection time step (**dtime**)
- treated in sequential-update split mode
  - model state is updated after each process

Physics-Dynamics coupling

- We distinguish between "fast physics" and "slow physics"
- On the basis of process time scales versus model time step
- Processes are treated isochorically (ρ=const, not p!)

Slow physics

- called every kth fast physics time step (k ≥ 1 is process dependent)
- treated in parallel-split split mode
  - all processes are computed from the same model state
- tendencies are passed to the dynamical core



The NWP physics package

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Process	Scheme	Settings
Radiation	RRTM **Not recommended** Mlawer et al. (1997), Barker et al. (2003)	`inwp_radiation=1`
	ecRad Hogan and Bozzo (2018)	`inwp_radiation=4`
Non-orographic gravity wave drag	Wave dissipation at critical level Orr et al. (2010)	`inwp_gwd=1`
Sub-grid scale orographic drag	Lott and Miller scheme Lott and Miller (1997)	`inwp_sso=1`
Microphysics	Single-moment scheme Doms et al. (2011), Seifert (2008)	`inwp_gscp=1, 2`
	Double-moment scheme Seifert and Beheng (2006)	`inwp_gscp=4`
new	Mixed-phase Spectral Bin Microphysics (SBM) Khain and Sednev (1996), Khain et al. (2004)	`inwp_gscp=8`

We 09:45

We 14:00

nwp_phy_nml

The NWP physics package

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Process	Scheme	Settings
Convection	Mass-flux shallow and deep Tiedtke (1989), Bechtold et al. (2008)	inwp_convection=1
Cloud cover	Diagnostic PDF *M. Köhler et al. (DWD)*	inwp_cldcover=1
	All-or-nothing scheme (grid-scale clouds)	inwp_cldcover=5
Turbulent diffusion	Prognostic TKE (COSMO) Raschendorfer (2001)	inwp_turb=1
	3D Smagorinsky diffusion (for LES) Smagorinsky (1963), Lilly (1962)	inwp_turb=5
Land	Tiled TERRA Schrodin and Heise (2001), Schulz et al. (2016)	inwp_surface=1
	Flake: Mironov (2008)	llake=.TRUE.
	Sea-ice: Mironov et al. (2012)	lseaice=.TRUE.

We 14:00

We 11:45

We 11:00

nwp_phy_nml

The NWP physics package

Process	Scheme	Settings
Convection	Mass-flux shallow and deep Tiedtke (1989), Bechtold et al. (2008)	inwp_convection=1
Cloud cover	Diagnostic PDF *M. Köhler et al. (DWD)*	inwp_cldcover=1
	All-or-nothing scheme (grid-scale clouds)	inwp_cldcover=5
Turbulent diffusion	Prognostic TKE (COSMO) Raschendorfer (2001)	inwp_turb=1
	Schrodin and Heise (2001), Schulz et al. (2016)	
	Flake: Mironov (2008)	llake=.TRUE.
	Sea-ice: Mironov et al. (2012)	lseaice=.TRUE.

We 14:00

We 11:45

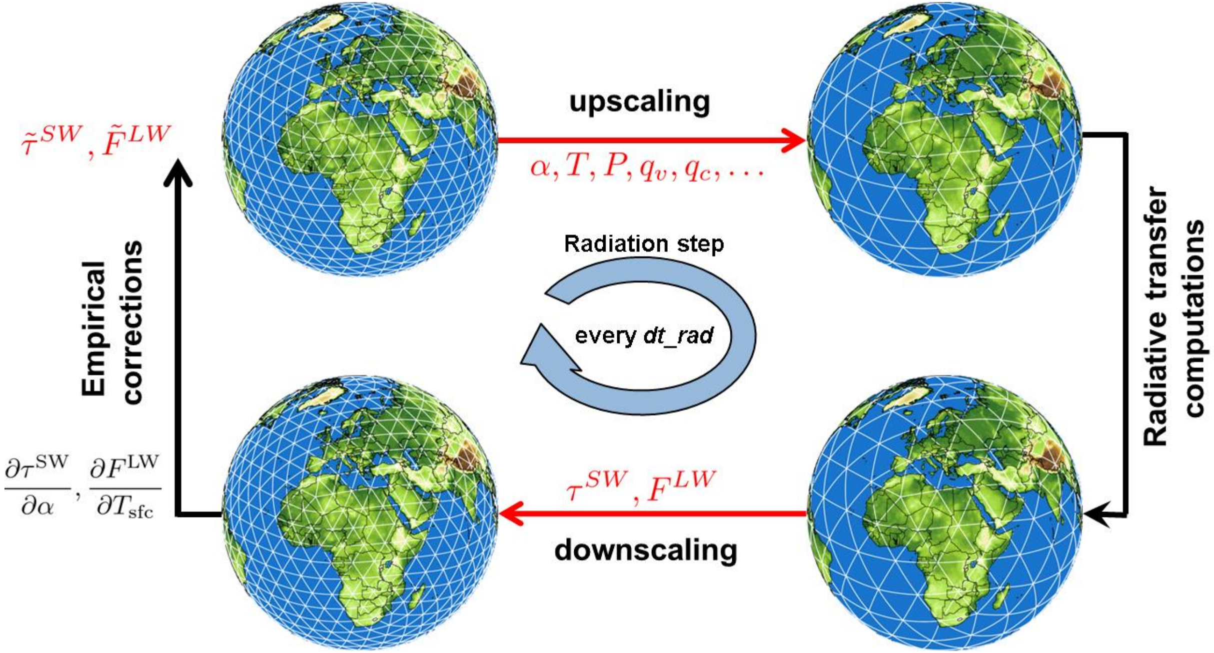
We 11:00

Warning!
Do not patch together randomly! Not all combinations are tested or even foreseen.
The model may crash without throwing a proper error message.

nwp_phy_nml

Reduced radiation grid

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



Example for R3B7 (13km)

- radiation: R3B6 (26km)
- Δt =120 s
- Δt_{rad} =1440 s

```
radiation_grid_filename
lredgrid_phys
(grid_nml)
```

Diffusion and Filters

Numerical Aspects of the ICON Atmosphere Model

Purpose of diffusion and filters

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

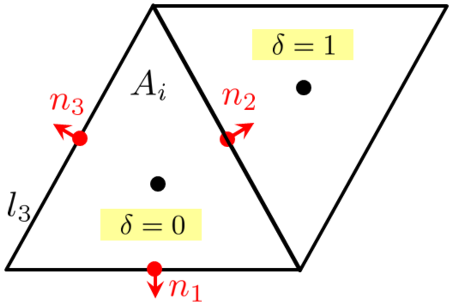
- All numerical **models need some form of dissipation** (either explicitly, or inherent in the numerical schemes)
- Dissipation may serve many purposes
  - removing numerical noise (due to dispersion errors, computational modes, initialization, grid-scale forcing from physics)
  - prevent the accumulation of energy at the grid scale
  - numerical stabilization
- Explicit diffusion/filters: extra terms (non-physical) added to the discrete momentum and thermodynamic equations

$$\frac{\partial \psi}{\partial t} = \mathrm{Dyn}(\Psi) + \mathrm{Phys}(\Psi) + F_{\Psi} \qquad \Psi = v_n, w, \theta_v, q_k$$

Checkerboard noise on triangular C-grids

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- **Triangular C-grid** suffers from **spurious computational mode** (e.g. Danilov (2010)), triggered by the discrete divergence operator (Wan et al. (2013))
- Divergence operator in ICON: applies the Gauss theorem



$$\operatorname{div}(\mathbf{v}) = \frac{1}{A_i}\sum_{e=1}^{3} v_{n,e}\,(\mathbf{N}_e \cdot \mathbf{n}_{i,e})\; l_e$$

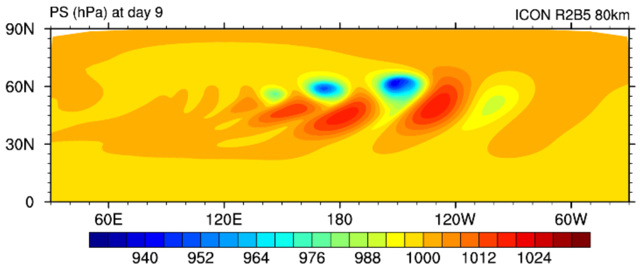
- Truncation error analysis:

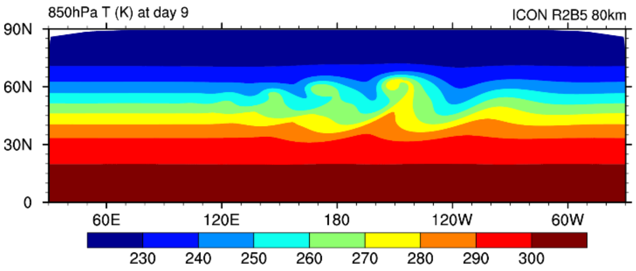
$$\operatorname{div}(\mathbf{v}) = \overline{(\nabla \cdot \mathbf{v})} + \boxed{(-1)^{\delta}}\, l\, H(\mathbf{v})_0 + \mathcal{O}(l^2)$$

  - Operator only **1st order** accurate on triangular C-grid
  - Error changes sign from upward- to downward pointing triangle ⇒ **checkerboard**

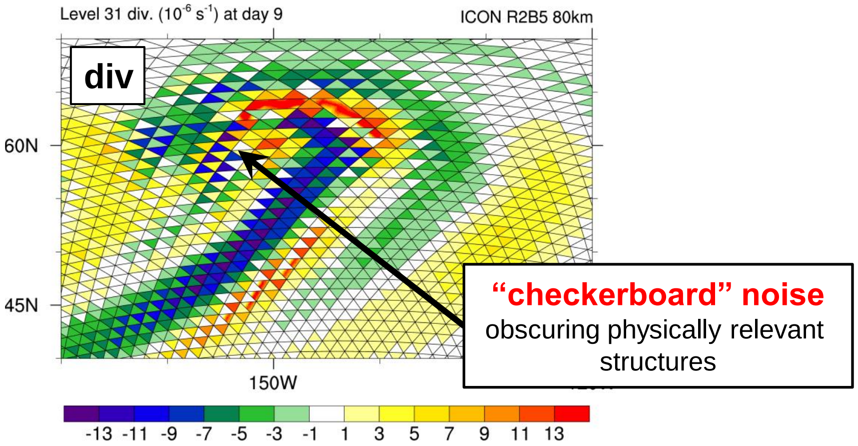
Example: Jablonowski baroclinic wave test

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

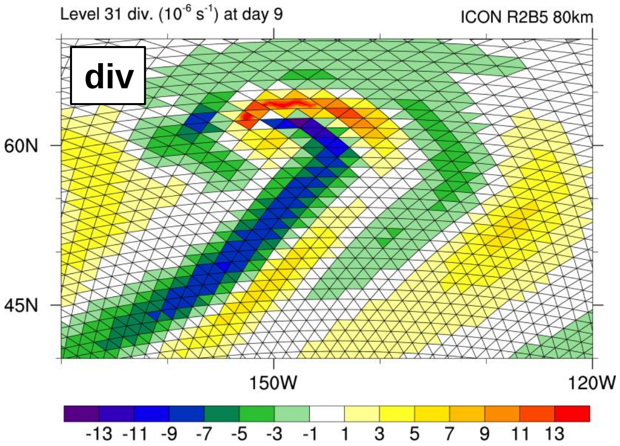




Standard divergence operator



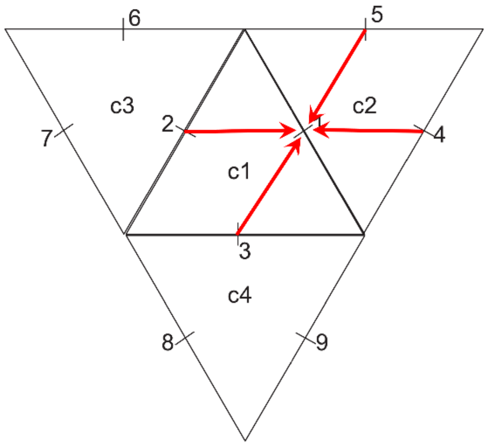
Improved divergence operator



Pragmatic solution: velocity averaging

- **Spatial averaging of the velocity components** that enter the divergence computation
- Achieves (almost) second-order accurate divergence operator
- **Loosely termed divergence averaging**
  (even though it is the velocity which is averaged)
- **unconditionally activated** in the dynamical core

5-point velocity averaging



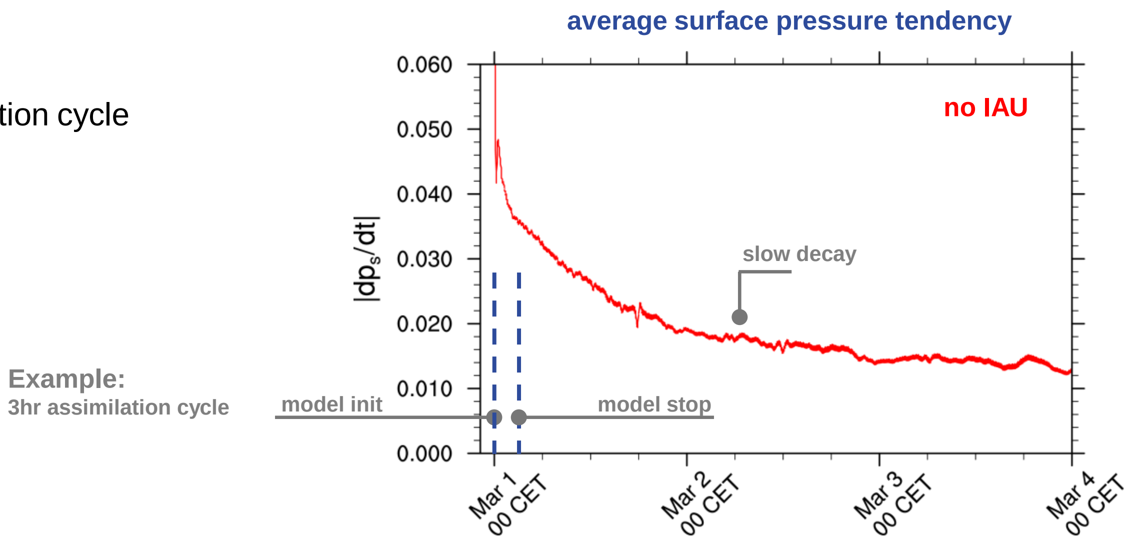
$$\mathrm{div}\,(\mathbf{v}) = \frac{1}{A_i} \sum_{e=1}^{3} v_{n,e} (\mathbf{N}_e \cdot \mathbf{n}_{i,e})\, l_e$$

For details see Zängl et al. (2015)

Incremental Analysis Update (IAU)

Problem

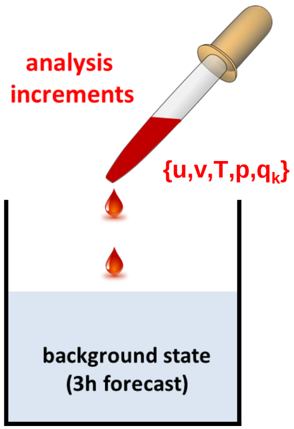
- Analysis fields (best guess of the atm. state) are not perfectly balanced.
- Leads to the generation of **spurious sound and gravity waves** in forecast runs.
- Decay timescale ≈ 1d (R3B7)
- Consequences:
  - accumulation of noise in the assimilation cycle
  - spin-up effects in forecast runs
- Filtering of initial conditions required



Incremental Analysis Update (IAU)

Solution

- **IAU**: Filtering procedure during model initialization
- Widely used at operational NWP centers
- Strategy:
  - analysis increments (FG - ANA) are added incrementally over many timesteps
  - filters small scale non-balanced modes (low pass filter)



model state vector | filter function | analysis increment

$$\frac{d\mathbf{x}}{dt} = \mathcal{A}\mathbf{x} + g(t)\Delta\mathbf{x}^A \qquad , \text{with} \quad \int g(t)\,dt = 1$$

phys + dyn

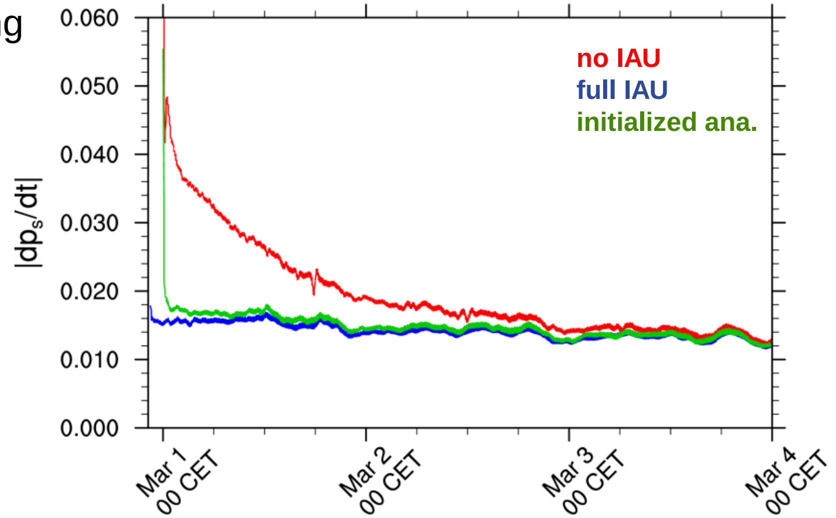
Tutorial
Sec 11.3

Example: global R3B7 forecast

```
Filter type : top hat
Filter width: 3h
Filter shape: symmetric about
              nominal start date
```

Incremental Analysis Update (IAU)

- IAU effectively damps small scale noise (blue)
- **DWD product “initialized analysis”** (= filtered analysis) (green)
- **Recommended** dataset **for initializing standalone forecast runs** (without data assimilation cycle)
- Noise level during spinup phase is somewhat larger than with full IAU cycle, but much smaller than when skipping IAU at all.
- **initialized analysis** available via the **PAMORE** web service for deterministic runs (see talk by Daniel Rieger).



Additional filtering mechanisms in ICON

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

- Linear horizontal (hyper)-diffusion
  - higher order (q>1) improves scale selectivity

```
hdiff_order
lhdiff_{temp,vn,w,q}
hdiff_xyz
(diffusion_nml)
```

diffusion coefficient

$$F_\Psi = (-1)^{q+1} K_{2q} \nabla^{2q} \Psi$$

for momentum and thermodynamic eqs.

- 2D/3D divergence damping
  - diffusion of the divergent part of the flow
  - 2D: reduces high-frequency gravity wave noise
  - 3D: acoustic mode filtering

```
divdamp_type
divdamp_order
damp_xyz
(nonhydrostatic_nml)
```

damping coefficient

$$\boldsymbol{F_v} = (-1)^{q+1} \nabla_{2/3} \left(\nu_{2q} \nabla_{2/3}^{2q-1} \cdot \boldsymbol{v} \right)$$

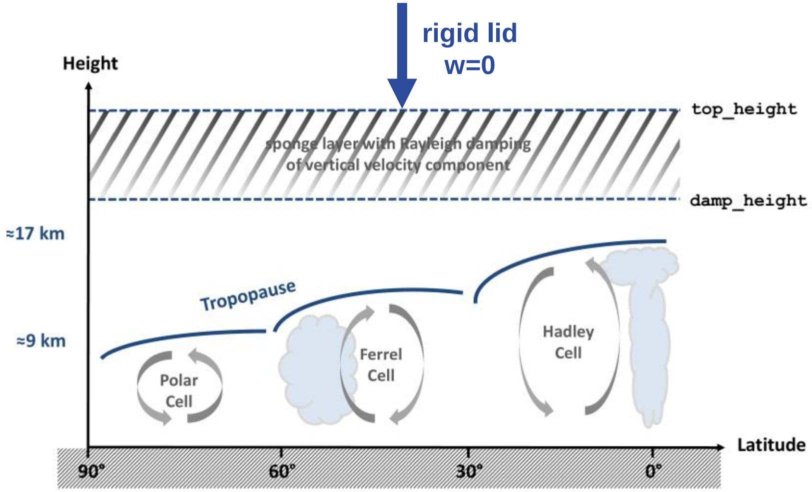
for momentum eq.

For details see Zängl et al. (2015)

Additional filtering mechanisms in ICON

- Sponge layer at model top
  - minimize spurious wave reflections at (rigid) model top by absorbing most of the incoming energy
  - acts by damping vertical velocity

```
rayleigh_type
rayleigh_coeff
damp_height
(nonhydrostatic_nml)
```



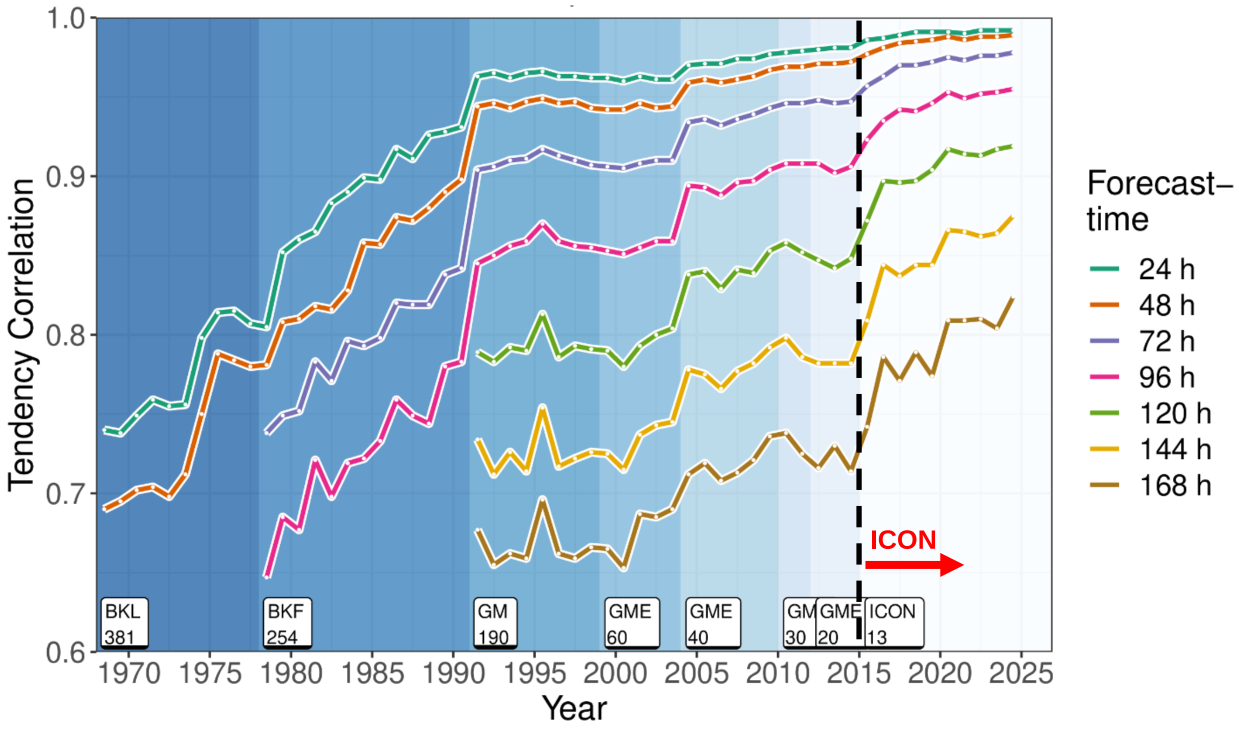
Progress in Forecast Quality

Numerical Aspects of the ICON Atmosphere Model

NWP forecast quality over time (1968-2024)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

Mean sea level pressure verification results for 1968 – 2024
Domain: northern Atlantic and Europe; Perfect: 1; fair: 0.6.



Progress in forecast quality (2020-2025)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

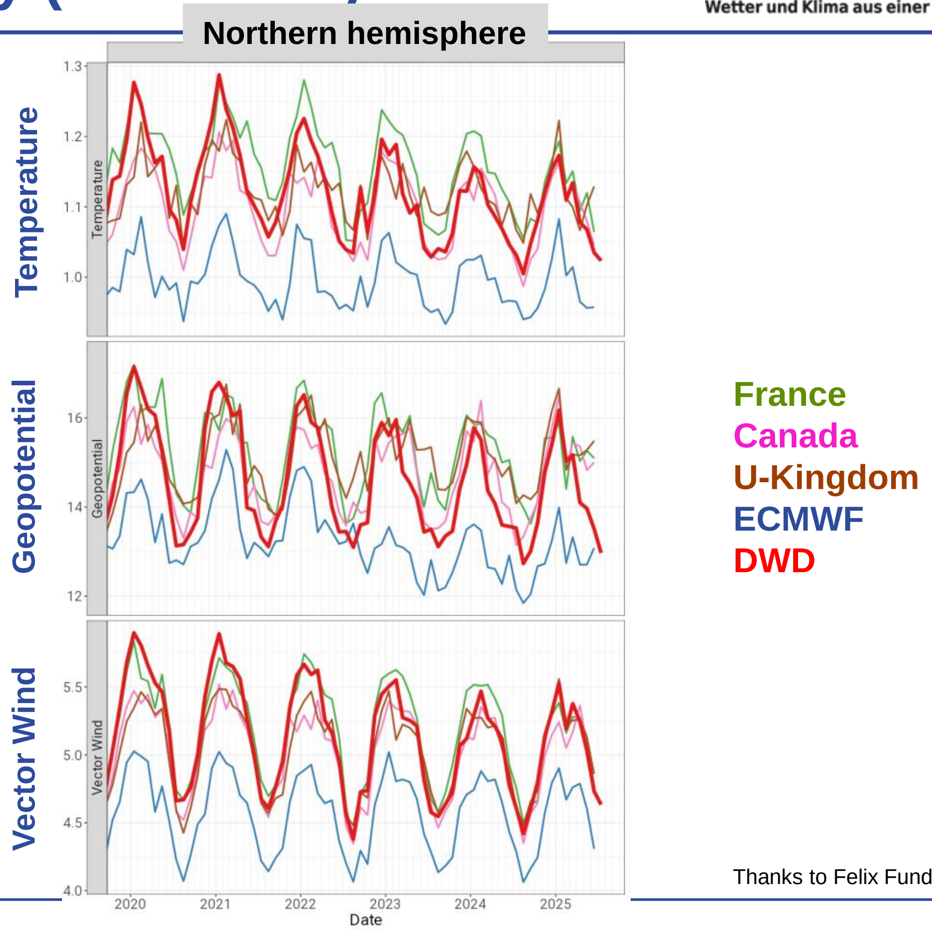
WMO verification against radiosondes

level: **500hPa**

lead-time: +**48h**

valid-time: 12UTC

score: **rmse**



Thanks to Felix Fundel (DWD)

Progress in forecast quality (2020-2025)

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

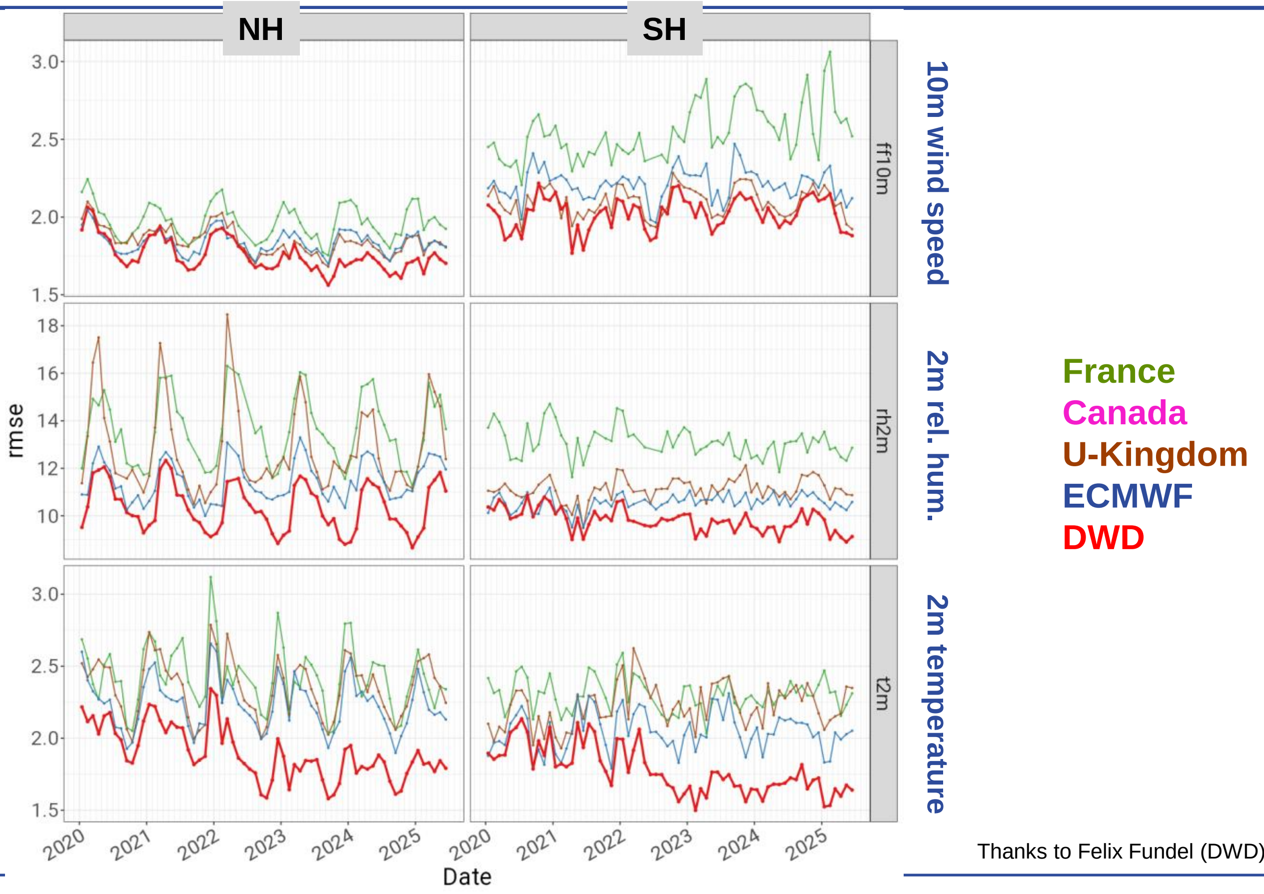
WMO verification against SYNOP

level: **surface**

lead-time: +**48h**

valid-time: 12UTC

score: **rmse**



Thanks to Felix Fundel (DWD)

Thank you for your attention

Daniel Reinert
Research and Development
daniel.reinert@dwd.de

Literature

Zängl et al. (2015): The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. Q.J.R. Meteorol. Soc., 141: 563-579. https://doi.org/10.1002/qj.2378

Leuenberger et al. (2010): A Generalization of the SLEVE Vertical Coordinate. Mon. Wea. Rev., 138, 3683–3689, https://doi.org/10.1175/2010MWR3307.1

Wan et al. (2013): The ICON-1.2 hydrostatic atmospheric dynamical core on triangular grids – Part 1: Formulation and performance of the baseline version, Geosci. Model Dev., 6, 735–763, https://doi.org/10.5194/gmd-6-735-2013

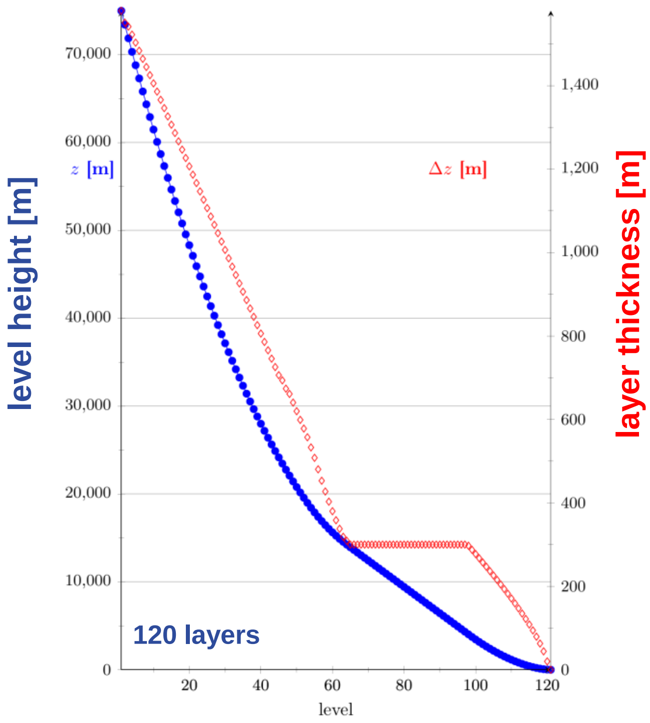
Danilov, S. (2010): On utility of triangular C-grid type discretization for numerical modeling of large-scale ocean flows. Ocean Dynamics 60, 1361–1369. https://doi.org/10.1007/s10236-010-0339-6

Prill et al. (2025): Working with the ICON Model, https://doi.org/10.5676/DWD_pub/nwv/icon_tutorial2024

Vertical grid

- For most NWP applications a **vertically stretched grid** is used.
- Layer thickness increases with height.
- Very small vertical aspect ratio $\Delta z/\Delta x \ll 1$
- Pancake-like prismatic cells

R3B7 (13km) DWD global setup



Main achievements …

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

… compared to previous global and regional NWP models at DWD

- **Better conservation** properties (local mass conservation)
  - flux form for prognostic quantities ρ and q_k
- Mass consistent tracer transport (tracer air-mass consistency)
- Applicability on a **wide range of scales** from ~100 km to ~100 m
  - fully compressible (nonhydrostatic) equation set
- **Scalability and efficiency** on massively parallel computer architectures with $O(10^4 +)$ cores
  - Fully explicit, local numerical methods
- Possibility of static **mesh refinement/nesting** (see upcoming talk)
- … and much **better quality** of operational weather forecasts