The ICON modelling framework of DWD and MPI-M

(Zängl et al. 2014)

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Outline

- Background and goals
- Horizontal and vertical grid
- Model equations
- Spatial discretization
- Temporal discretization
- Damping and diffusion
- Physics dynamics coupling
- Efficiency and scalability
- Applications
- Summary and References

Background

- ICON is developed by the German Weather Service (DWD) and the Max Planck Institute for Meteorology (MPI-M).
- **Weaknesses of the existing models** GME and ECHAM:
  - Hydrostatic dynamics
  - No local mass conservation
  - Limited parallelization / scalability
- **Towards a "unified" model system** to benefit from combining the expertise and applications fields of both insititutions:
  - DWD: Assimilation system, weather time scale, resolution ~10 km, Global or regional atmospheric models
  - MPI-M: Boundary conditions, years to millennia, resolution ~100 km, Earth system model

Goals

- **Non-hydrostatic** atmospheric model for:
  - High resolution NWP
  - Research: interaction of clouds and circulation
- Domains
  - Global or regional
  - Option for grid refinement → Nested regions
- **Local mass conservation** for tracers and total air mass
- Numerical methods must be **robust** and **fast** and should not hinder high **scalability** (strong and weak) on large computers.
- **Flexibility** for operational and research application.

Horizontal grid

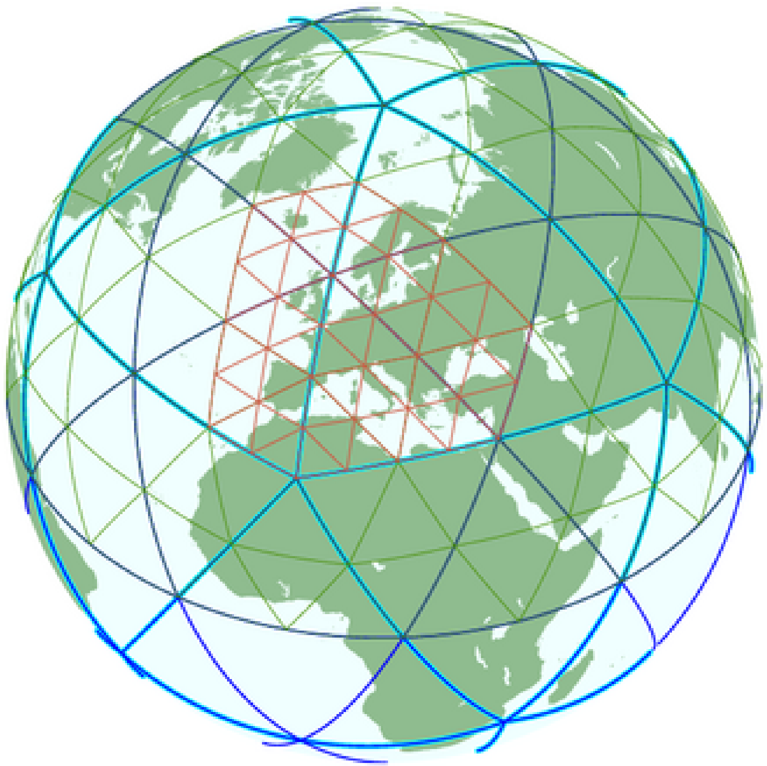
Icosahedral triangular grid

- Fairly uniform resolution on sphere
- Simple regional grid refinement

Example:

- Icosahedron
- Root division: 2 or more sections
- 1st follow-up bisection in NH
- 2nd follow-up bisection in Europe

Optimization by spring dynamics
(Tomita et al. 2001)



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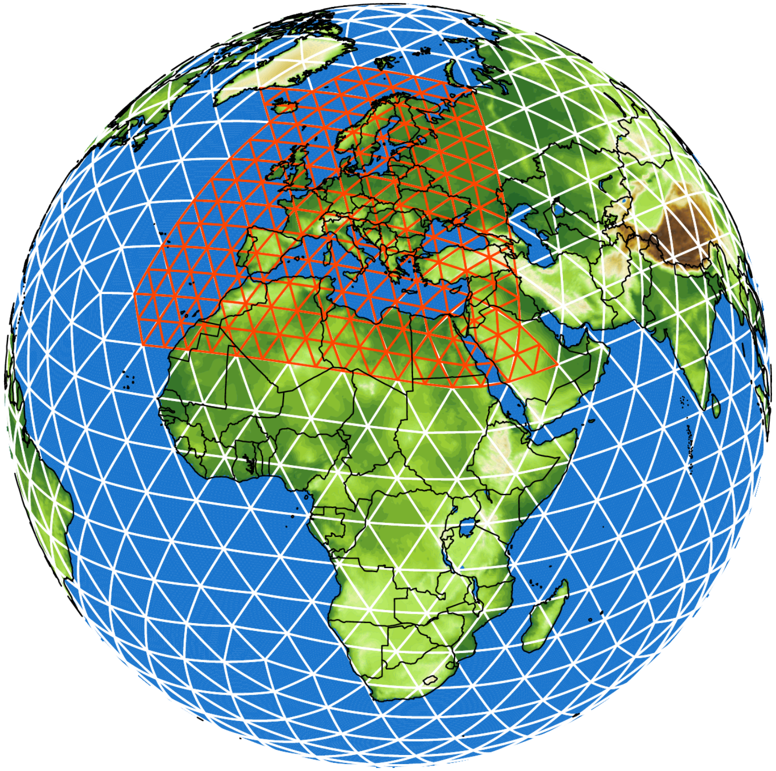
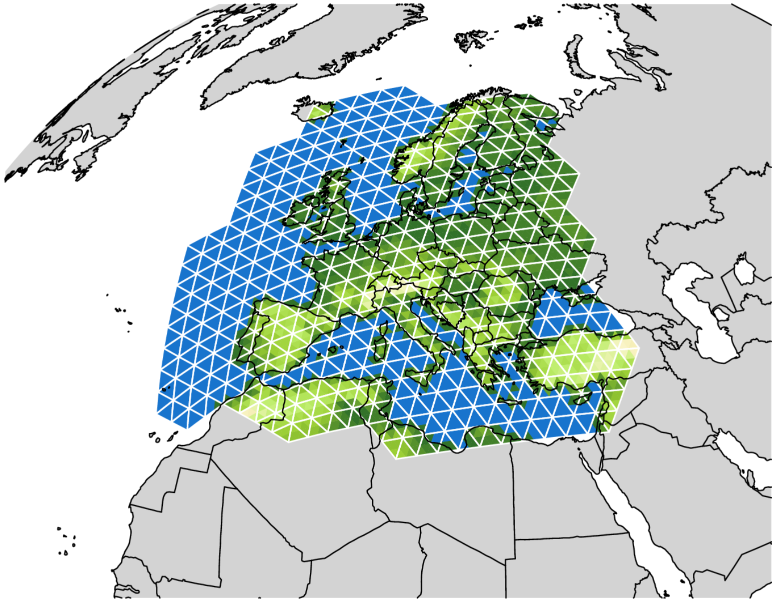
Example grids

Global grid + nested Europe region similar to NWP setup at DWD



Regional grid over Europe



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Vertical grid

- Generalized height based coordinate
- Smooth-level terrain following (Leuenberger et al., 2010)

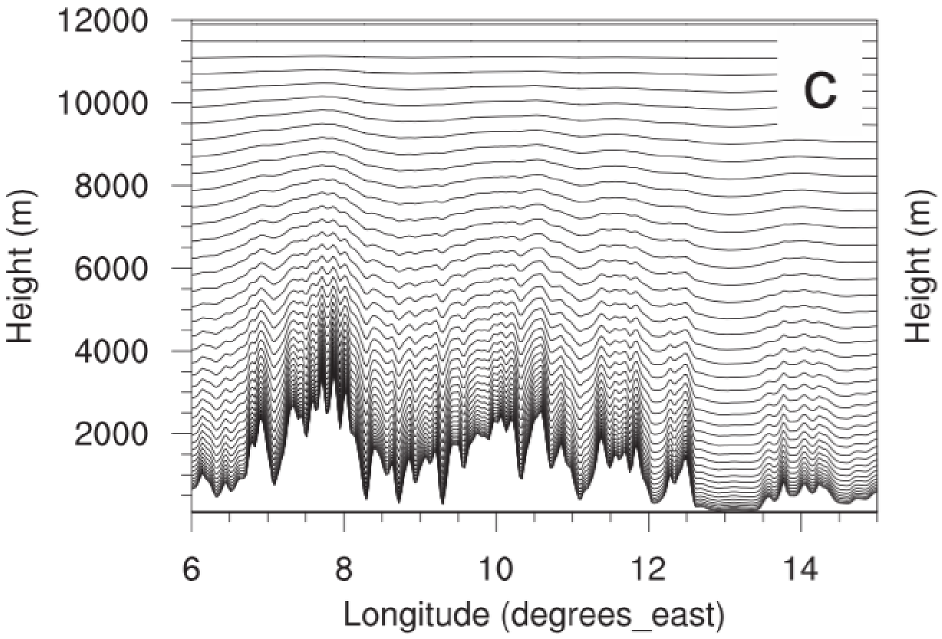

Fig. 6. Vertical cross section across the Alps.

Short/rough scales of the topography decay faster with altitude than smoothed scales.

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Model equations

- Fully compressible equations for a shallow atmosphere
- Vector invariant (cf. Gassmann and Herzog, 2008)
- Prognostic variables: v_n, w, ρ, θ_v and π, q

$$\frac{\partial v_\mathrm{n}}{\partial t} + \frac{\partial K_\mathrm{h}}{\partial n} + (\zeta + f)v_\mathrm{t} + w\frac{\partial v_\mathrm{n}}{\partial z} = -c_\mathrm{pd}\theta_v\frac{\partial \pi}{\partial n} + F(v_\mathrm{n}),$$

$$\frac{\partial w}{\partial t} + \mathbf{v_h}\cdot\nabla w + w\frac{\partial w}{\partial z} = -c_\mathrm{pd}\theta_v\frac{\partial \pi}{\partial z} - g,$$

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

$$\frac{\partial \rho\theta_v}{\partial t} + \nabla\cdot(\mathbf{v}\rho\theta_v) = \tilde{Q}. \qquad \pi = \left(\frac{R_\mathrm{d}}{p_{00}}\rho\theta_v\right)^{R_\mathrm{d}/c_\mathrm{vd}}$$

$$\frac{\partial \rho_m q}{\partial t} + \nabla\cdot(\rho_m q\,\boldsymbol{v}) = P_{\rho_m q}\ ,$$

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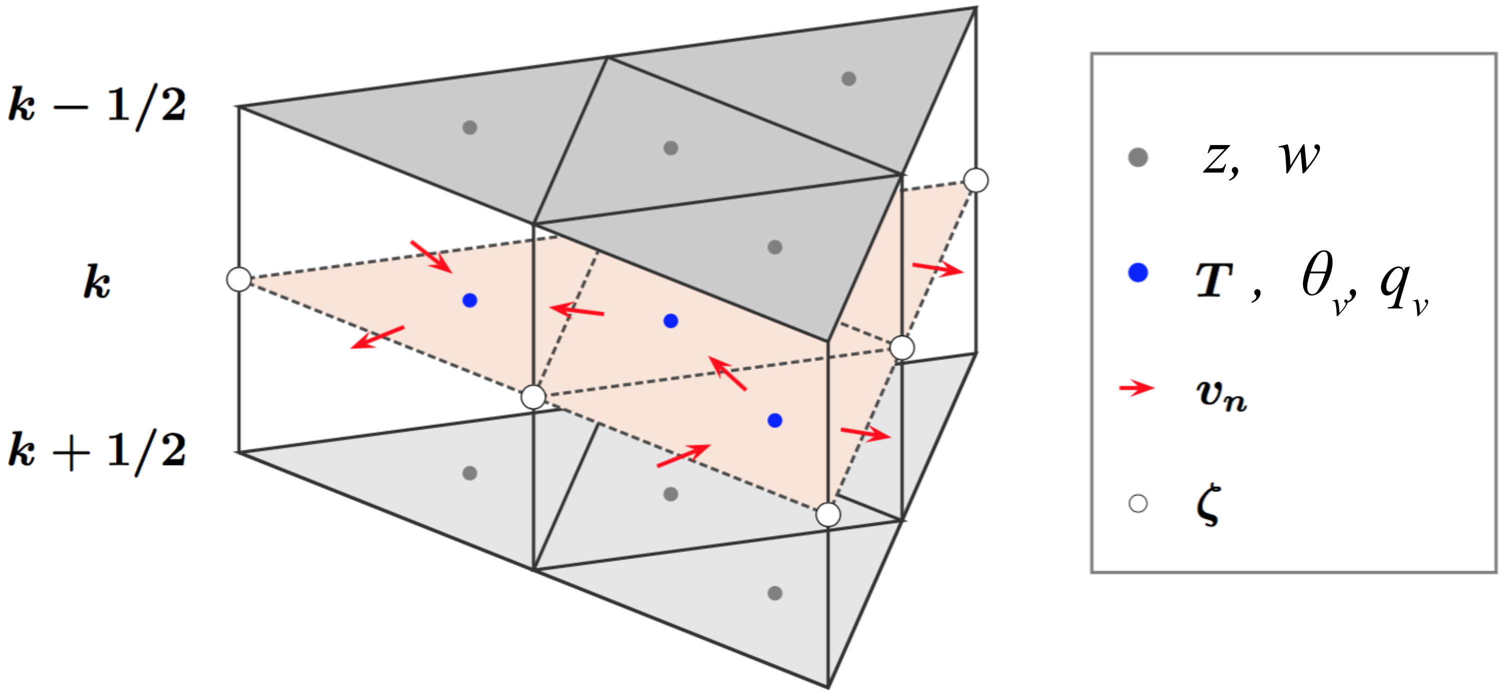
Spatial discretization: staggering

- Arakawa C grid discretization:



Adapted from Wan et al. (2013), Fig.1

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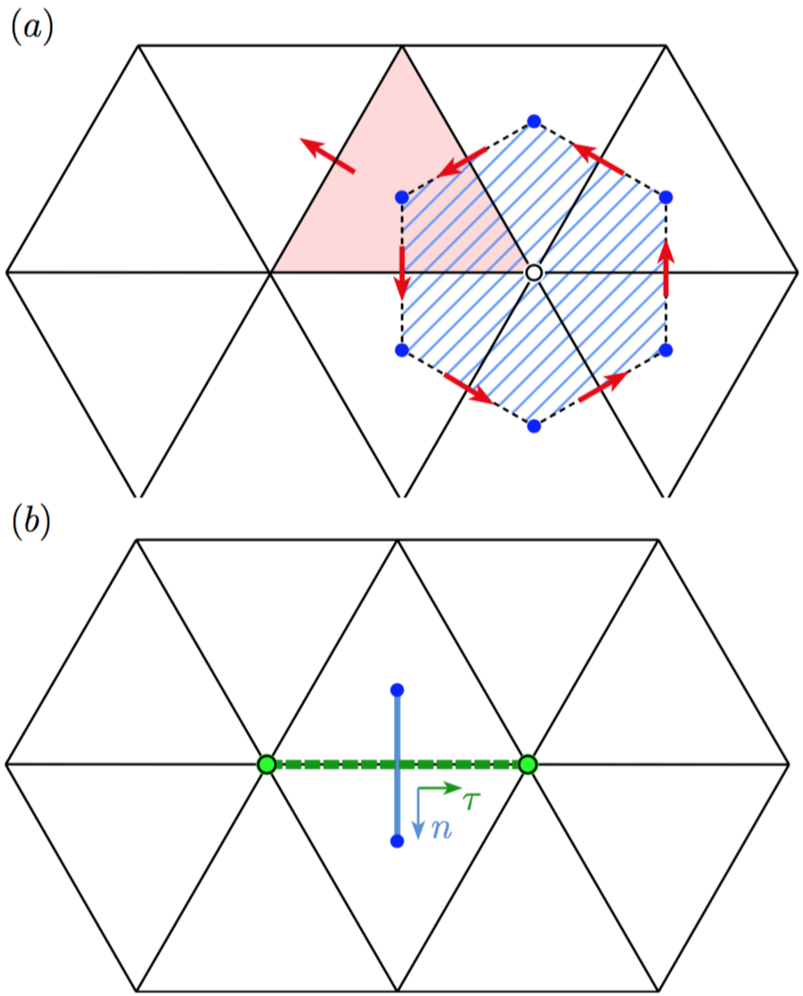
Spatial discretization: operators



Divergence operator:
Gauss theorem on triangular control volume

Curl operator for vorticity:
Stoke's theorem on dual cell (hexagon or pentagon)

Normal gradient operator:
Finite difference

Tangential gradient operator:
Central difference

Bonaventura and Ringler (2005), Wan et al. (2013), Fig. 2.

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Temporal discretization

- **Two-time-level predictor – corrector scheme**
- **“HEWI”:** Explicit except for terms describing vertical sound wave propagation
- **Time splitting** between the dynamical core and horizontal diffusion + tracer advection + fast physics
- **Mass-consistent transport** is achieved by passing time-averaged air-mass fluxes from the dynamical core to the transport scheme.
- Typical time step ratio:
  5 dynamics sub-steps : 1 transport/physics step

Damping and diffusion

Damping at dynamics time step

- 4th order divergence damping of v_n
- Rayleigh damping on w following Klemp et al. (2008) to prevent reflections of gravity waves at the model top.

Diffusion at physics time step

- 2nd order Smagorinsky diffusion of v_n and θ_v combined with
- 4th order background diffusion of v_n.
- (4th order diffusion on w for resolutions dx < 1km)

Used in “SCELL”

Physics dynamics coupling

- **At constant density (volume)** rather than constant pressure
  → Use c_v for temperature tendencies.
- **Physics uses hydrostatically integrated pressure** rather than a non-hydrostatic pressure derived directly from the prognostic model variables.
- For efficiency, a distinction is made between so-called **fast-physics processes** and **slow-physics** processes.
- **Fast physics processes** are treated with **operator splitting**, acting on the provisional atmospheric state that has already been updated by **dynamics, diffusion, and transport.**
- **Slow physics processes** provide **forcing terms to the dynamical core** that remain constant for all dynamic sub-steps.

Fast and slow physics for NWP

- **Fast physics:** updates sequentially after dynamics, using provisional states
  1) saturation adjustment
  2) surface transfer scheme
  3) land-surface scheme
  4) boundary-layer/turbulent vertical diffusion scheme
  5) microphysics scheme
  6) saturation adjustment

DCMIP physics = fast physics

- Slow physics: provides forcing to dynamical core, using final state
  - Radiation
  - Convection
  - Subgrid scale orographic effects
  - Non-orographic gravity waves

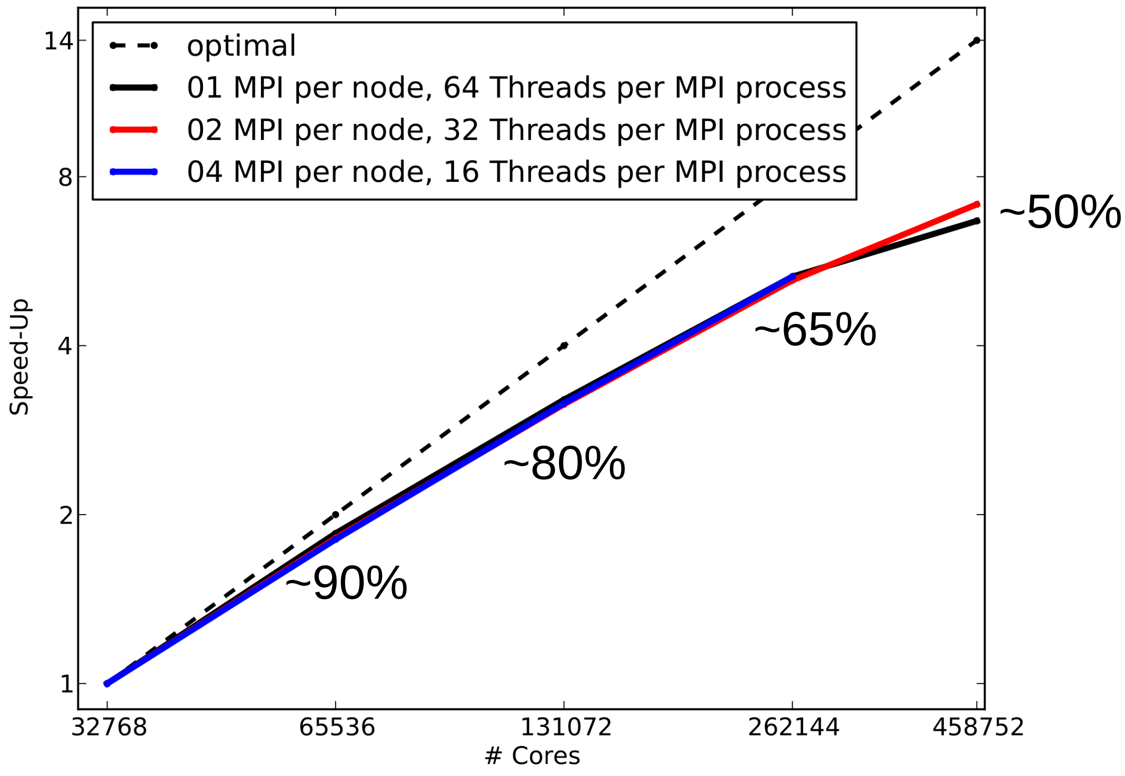
Efficiency and Scalability

- Use simple operators / procedures where possible
- Only next neighbor communication

Strong scaling test for
a large eddy simulation
on BlueGene/Q (JUQUEEN),

Timing excludes I/O.

Minimum of 32768 cores
needed for memory.



www.fz-juelich.de/ias/jsc/EN/Expertise/High-Q-Club/ICON/_node.html

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Applications

- Operational weather forecast at DWD
  - 13 km global resolution + 6.5 km in nested European region
- Climate research
  - Real world “AMIP” simulations for 1979-2008, at 160 km or 40 km res.
  - Aqua and Terra planet experiments
  - Radiative – convective equilibrium on planet or double periodic plain
  - Large eddy simulations (~100 m resolution)
- Under development
  - Coupled model for climate simulations and
    seasonal to decadal forecasting
    ICON atmosphere + ICON ocean + YAC coupler

Summary

- Global non-hydrostatic atmosphere
- Icosahedral triangular C-grid +
  smoothed terrain following z coord.
- Locally mass conservation
- Flux form continuity equation with ρ as prognostic variable
- Flux form semi-Lagrangian tracer transport
- Two time level predictor corrector scheme, fully explicit
  except for terms describing vertical sound waves
- Time splitting between the dynamics and
  transport + horizontal diffusion + fast physics.
- Focus on efficiency and scalability

References

Zängl, G., D. Reinert, P. Ripodas, and M. Baldauf (2014), 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. http://onlinelibrary.wiley.com/doi/10.1002/qj.2378/full