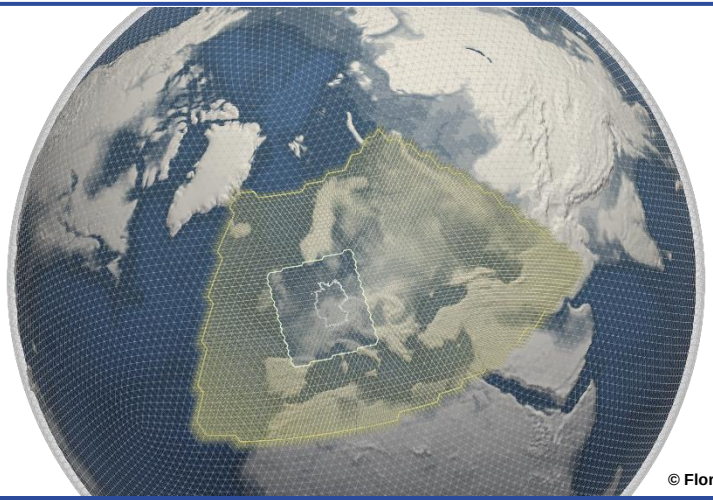

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Grid Nesting and Limited Area Mode

Daniel Reinert, Günther Zängl, Florian Prill

Deutscher Wetterdienst, Offenbach

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

Outline

Grid nesting in ICON

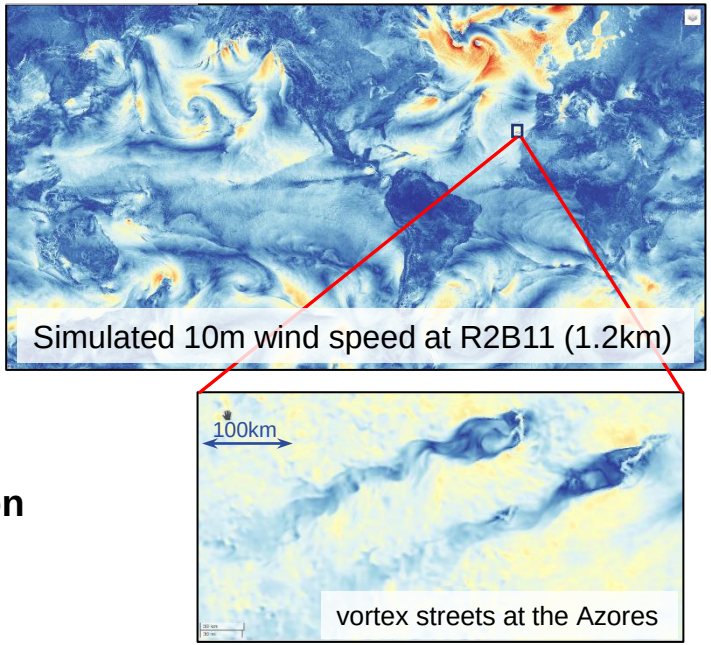
- *Basic concept*
- *Technical implementation*
- *Application examples*
  - *Idealized baroclinic wave with nests*
  - *Operational NWP application*

Limited Area Mode (LAM)

- *Necessary input data*
- *Boundary nudging*
- *Pros and Cons compared to nesting*

Why is Nesting or LAM still a Desirable Feature?

- Nowadays convection permitting simulations at global scale are technically feasible.
- … but still impractical to do on a daily basis.
- Challenges: time to solution, data processing, …

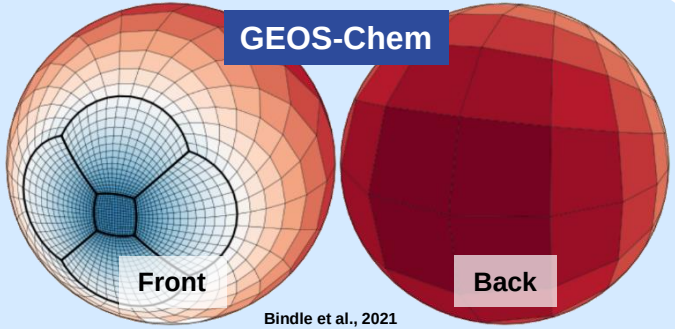


- A global model which is capable of **running at high resolution only in selected regions** is still **desirable**.
- Possible techniques:
  - **Grid refinement/nesting**
  - **Limited area mode**

Grid Nesting in ICON

Grid Nesting and Limited Area Mode

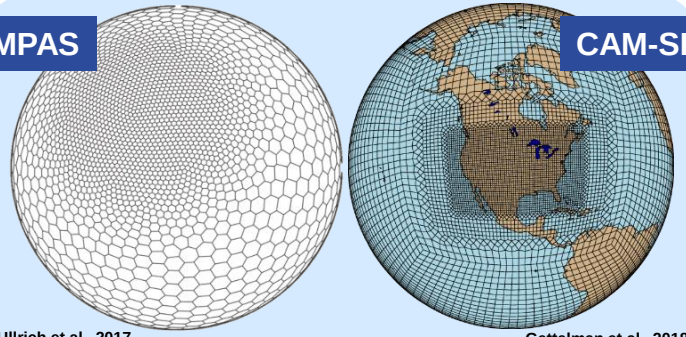
Grid Refinement Techniques in Atm. Models



Bindle et al., 2021

Grid stretching

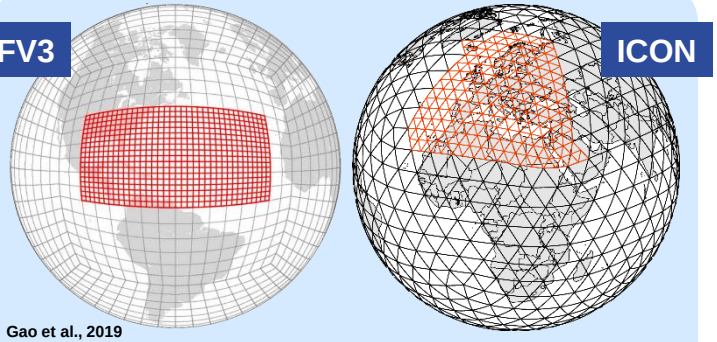
seamless refinement (single grid)



Ullrich et al., 2017

Gettelman et al., 2018

Local refinement



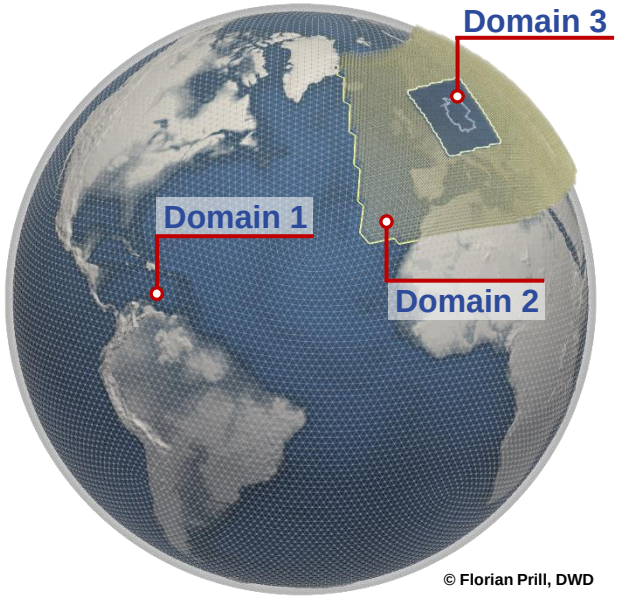
Gao et al., 2019

Grid nesting

series of nested domains (multiple grids)

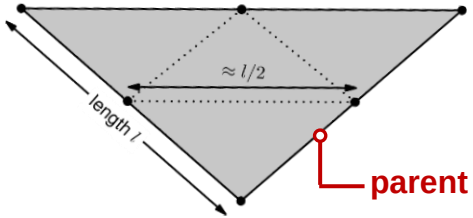
Note: focus on **static** refinement

Grid Nesting in ICON – Basic Concept



Nested setup with 3 domains
(3 distinct grid files)

- fixed refinement ratio of 2!



- time step for the child domain gets multiplied by 0.5 automatically

```
dtime (run_nml)
```

- one-way and two-way nesting is possible
  - one-way: parent domain ‘does not know’ about existence of child domain
  - two-way: parent domain gets feedback from child domain

```
lfeedback (grid_nml)
```

Tutorial
Sec 3.9

How to Activate One or More Nested Domains

Let us assume that **grid files** and **external parameter files** have already been **generated**:

→ **Zonda:** ICON Grid & ExtPar interface

```
&grid_nml
 dynamics_grid_filename = 'grid_DOM01.nc','grid_DOM02.nc',...
 lfeedback              = .TRUE.,  ...
 ...
/

&extpar_nml
 extpar_filename        = 'extpar_DOM<idom>.nc'
 ...
/

&initicon_nml
  dwdfg_filename        = 'dwdANA_DOM<idom>.grb'
/

&run_nml
 num_lev                = 90, 60, ...
 lvert_nest             = .TRUE.
 ...
/
```

keyword

add new grid file(s) to the list of computational domains

specify if nest(s) shall be one-way or two-way coupled

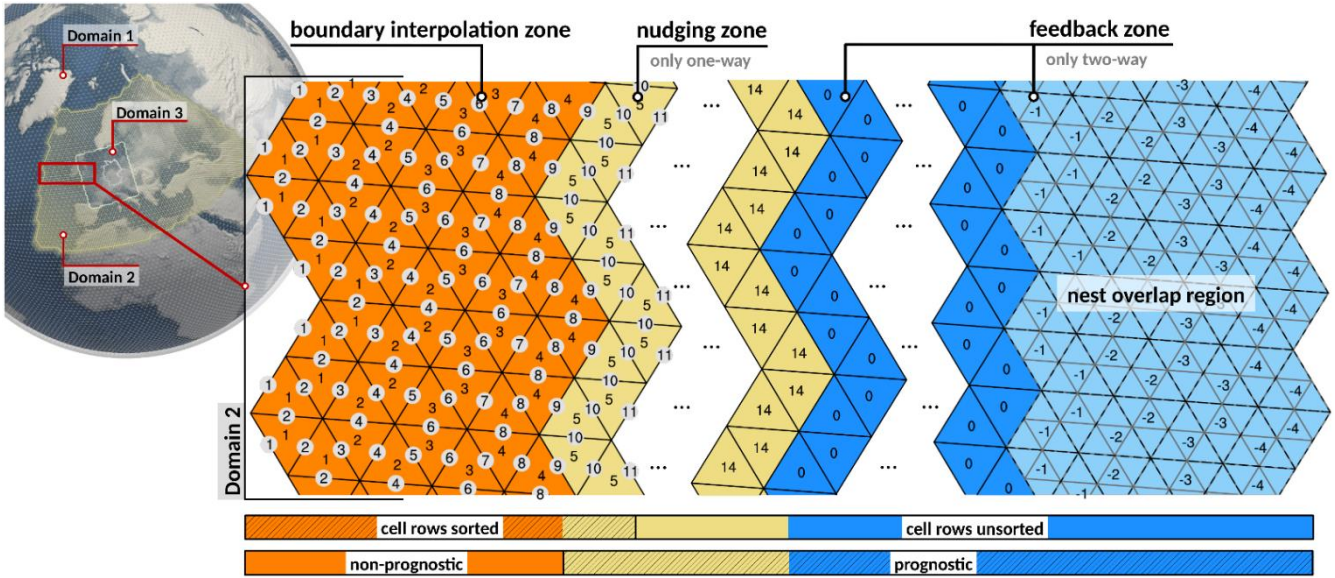
add the external parameter file(s)

add the initial condition(s) file

optional: specify the number of vertical levels

Tutorial p. 150
for list of keywords

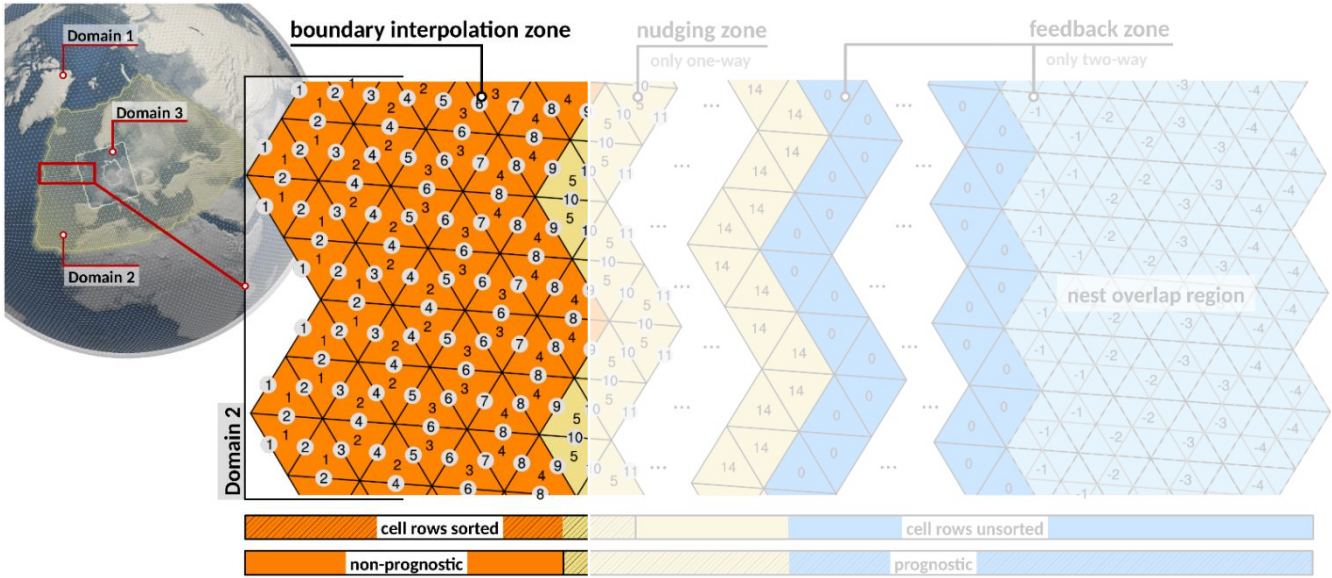
General Structure of a Nested Domain



A nested domain is split into **3 zones**, in order to accomplish the parent-child coupling:

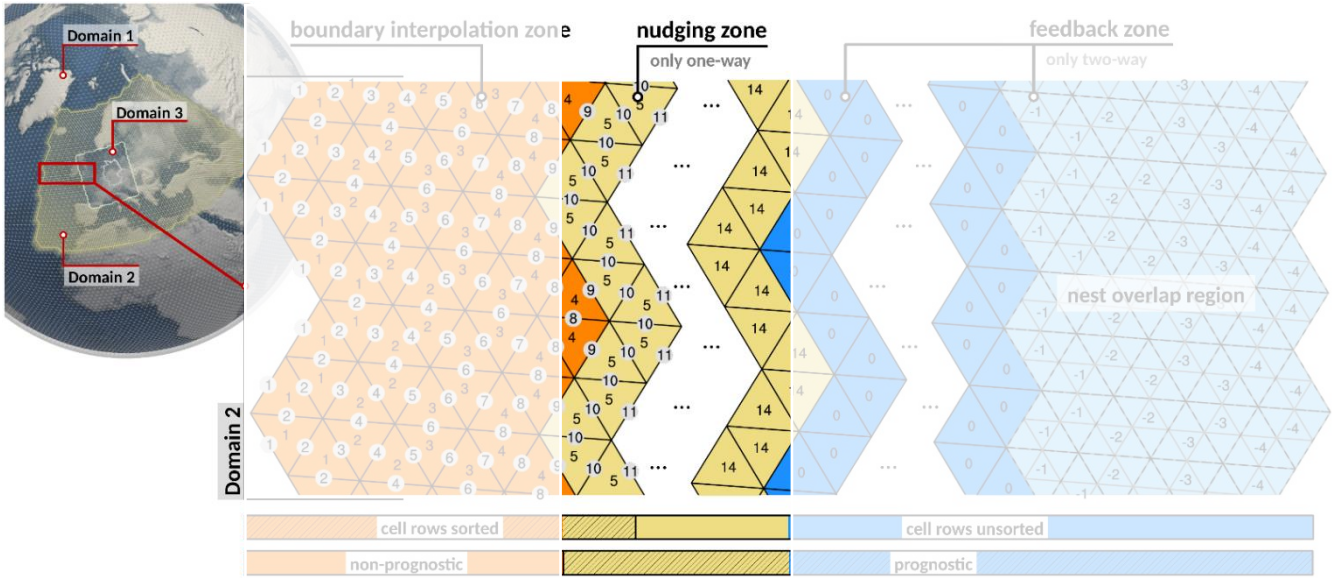
- the boundary interpolation zone **(orange)**
- the nudging zone **(ocher)**
- the feedback zone **(blue)**

Boundary Interpolation Zone



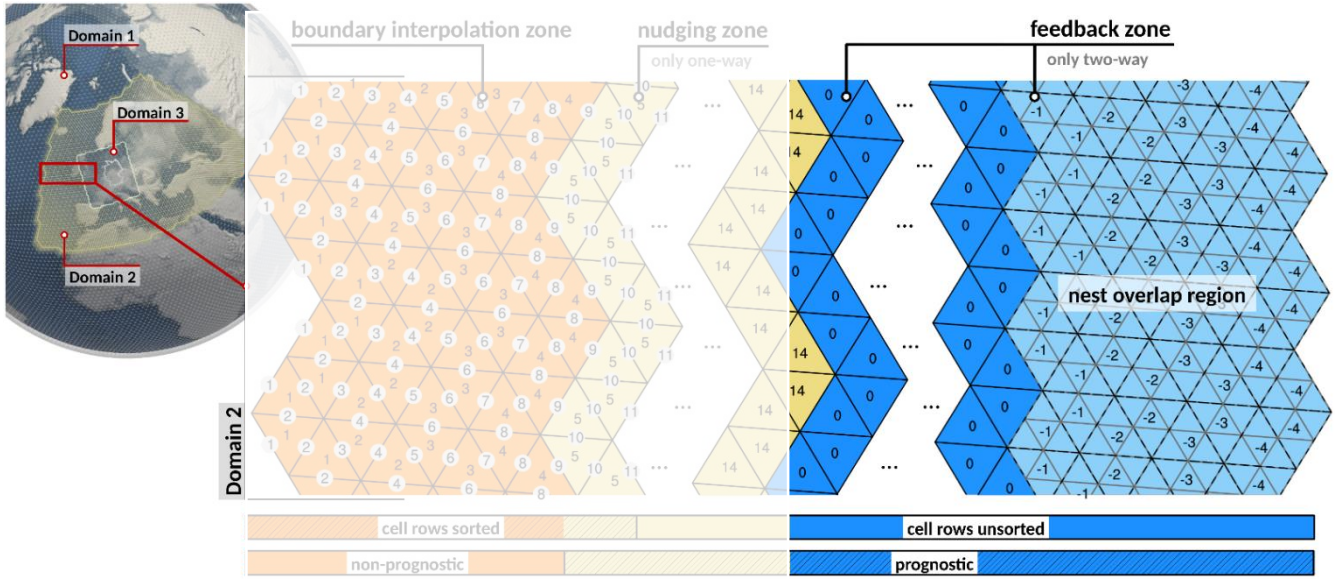
- **establishes parent-to-child coupling**
- **receives** interpolated **boundary conditions from** the **parent** domain at every parent time step, to solve the governing equations in the child domain.
- fixed width of 4 cell rows

Nudging Zone



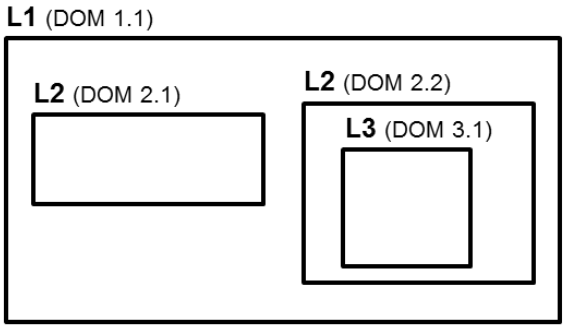
- **damps differences** between the driving solution in the boundary interpolation zone and the prognostic solution in the domain interior.
- only active for one-way nesting or LAM

Feedback Zone



- **establishes the child-to-parent coupling (feedback)**
- child solution is fed back to the parent domain at every (parent) time step.
- **relaxation-type feedback with adjustable timescale** rather than direct feedback.
- feedback of atm. variables only: **VN, W, THETA_V, DEN, QV, QC, QI**

Additional Features

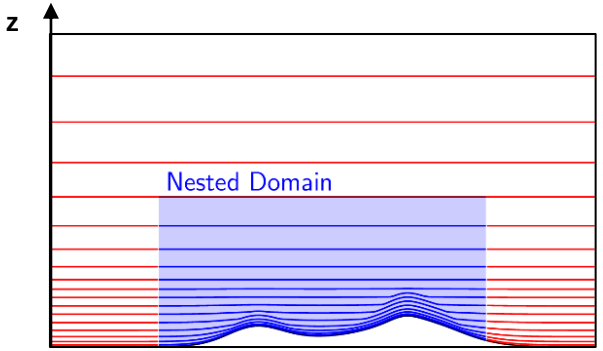


- multiple nesting (telescoping)
- mixing of one-way and two-way nested domains

```
lfeedback (grid_nml)
```

- nests may be switched on or off during runtime (lazy initialization mode)

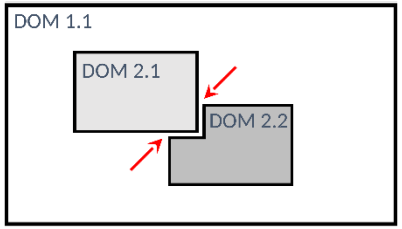
```
start_time (grid_nml)
end_time
```



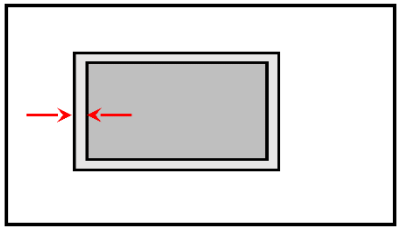
- **vertical nesting**
- nested domains may have lower top heights
- **vertical refinement** in the child domain is **not implemented**

```
lvert_nest (run_nml)
num_lev
```

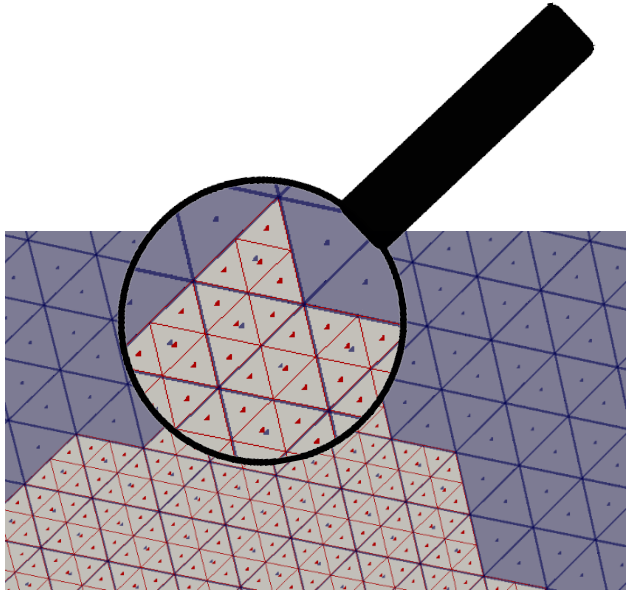
Technical Limitations and Caveats



- domains of the same nesting level **must not overlap** (the grid generator takes care of it)



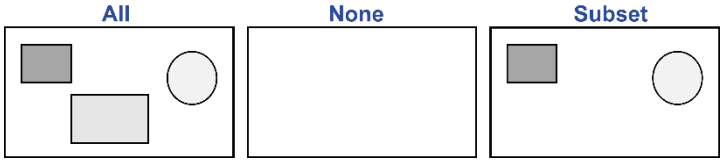
- telescoping: the child domain **must be smaller** than the parent domain (by 4 cell rows at least)



- **child cell circumcenters** do not necessarily coincide with parent cell circumcenters (grid optimization)

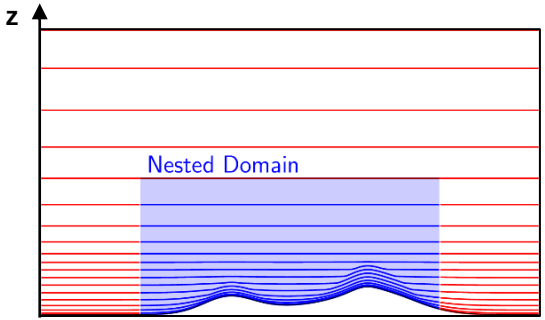
Connectivity Information

- A **child grid (file) contains connectivity information** about its parent grid, but not the other way around!
- This allows to
  - a posteriori create new child grids for existing grids
  - do model runs using either all, none, or a subset of available child grids.



Flexible child domain selection

- There exists no parent-child connectivity information in the vertical.
  - it is implicitly assumed that vertical cell interface heights match exactly between parent and child grids. **Approximation!!**
  - no vertical remapping during child-to-parent feedback

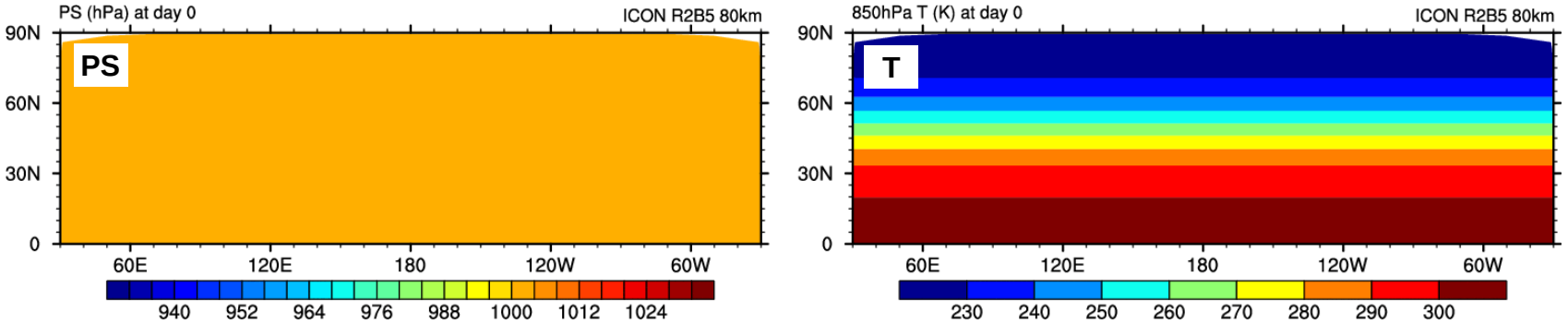


In complex terrain, vertical level heights differ (slightly) between parent and child

Application Examples

Grid Nesting and Limited Area Mode

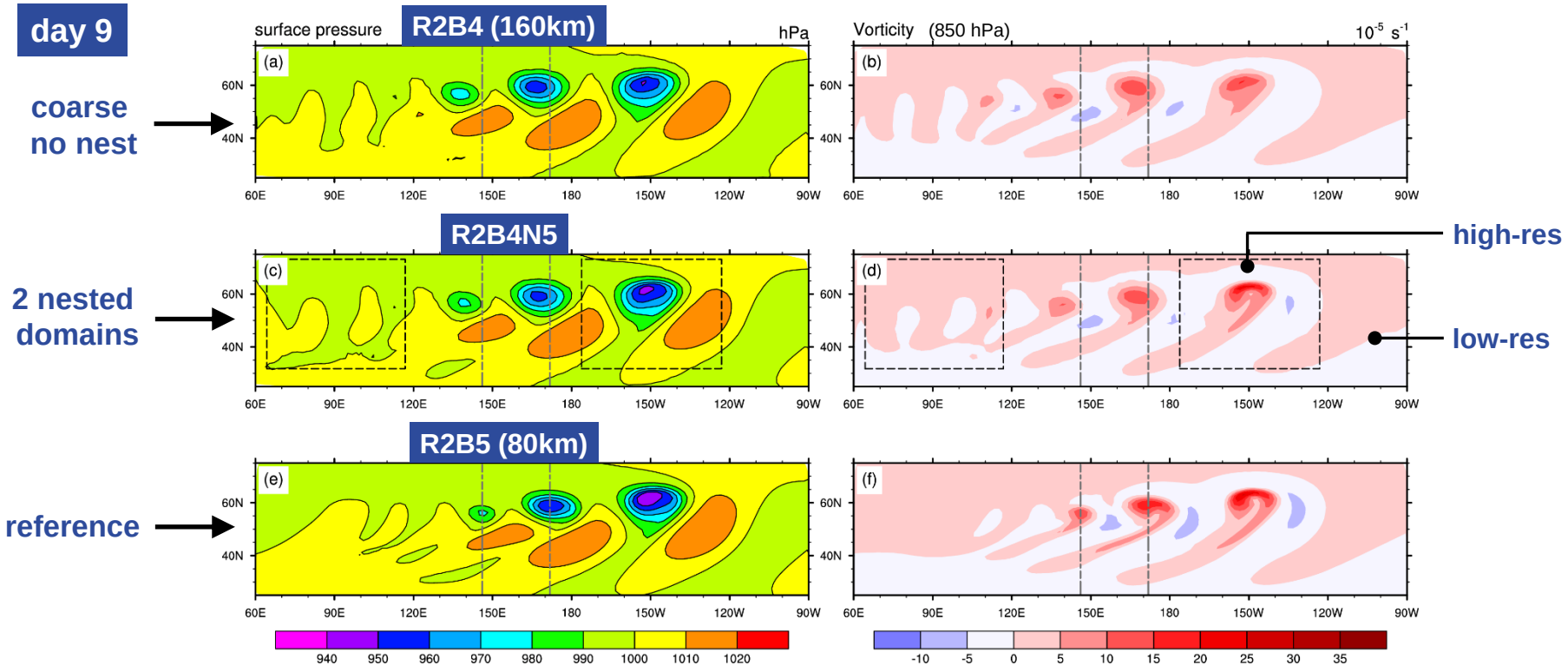
Example: Idealized Baroclinic Wave Test



We have used this test in the past in order to:

- validate the functionality of the grid nesting
- investigate numerical artefacts related to the resolution jump along nest boundaries

Idealized Baroclinic Wave Test with Nests



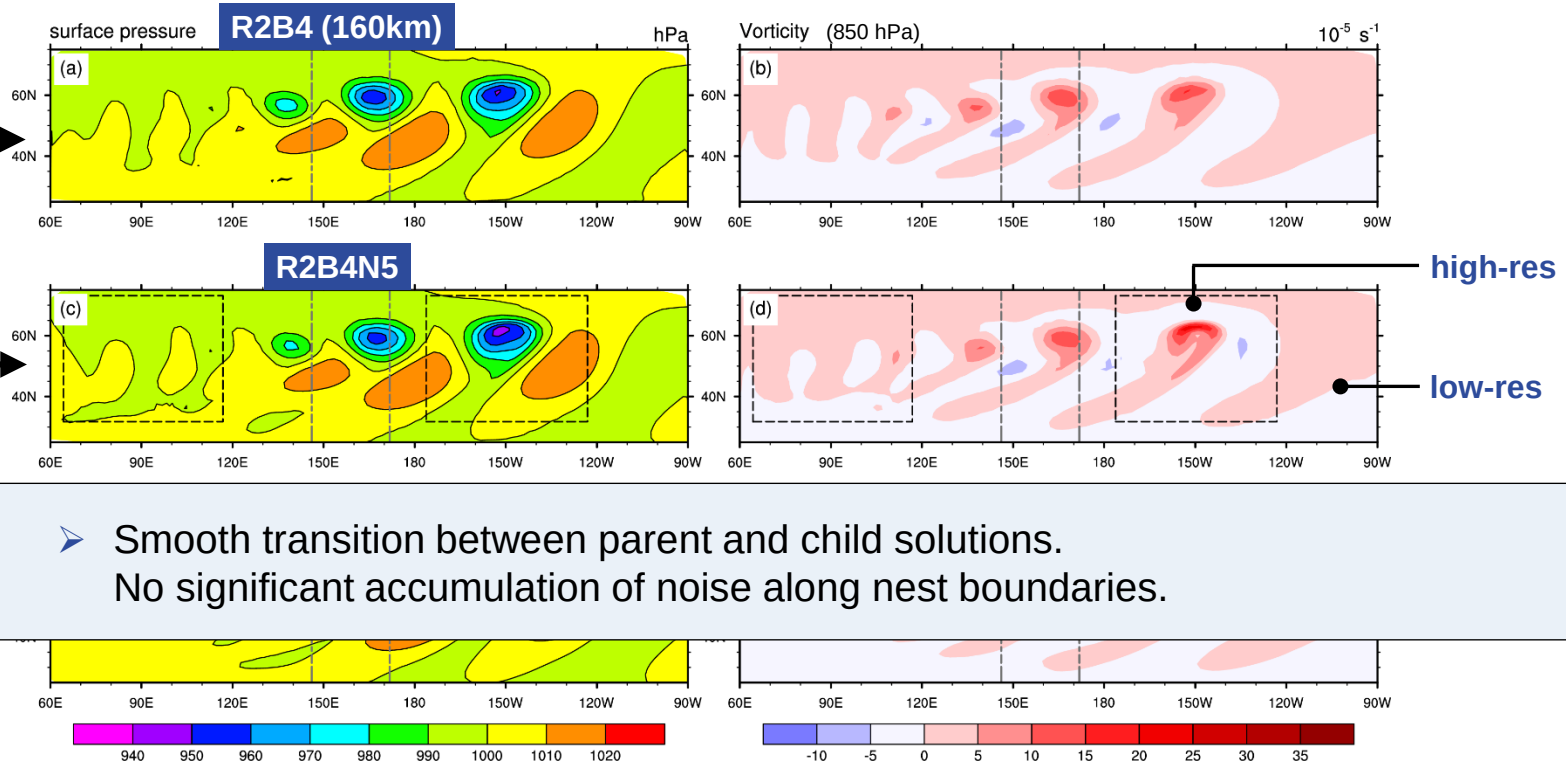
Idealized Baroclinic Wave Test with Nests

Deutscher Wetterdienst
Wetter und Klima aus einer Hand

day 9

coarse no nest

2 nested domains

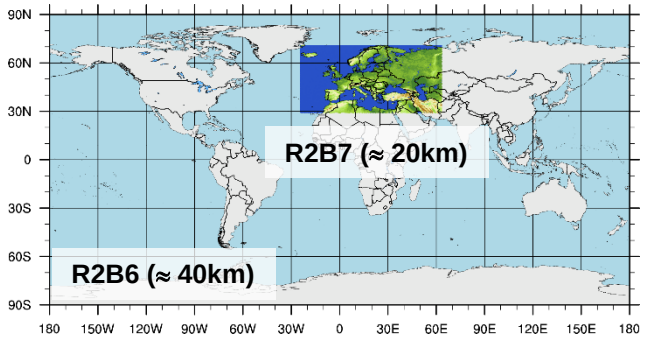


- Smooth transition between parent and child solutions.
  No significant accumulation of noise along nest boundaries.

Example: Operational NWP Application

Does a two-way nest over Europe have a beneficial impact on global forecast quality?

Nested configuration (two-way)



	global	nest
hor. resolution	40 km	20 km
levels	90	60
top height	75 km	23 km
lead time	180 h	120 h

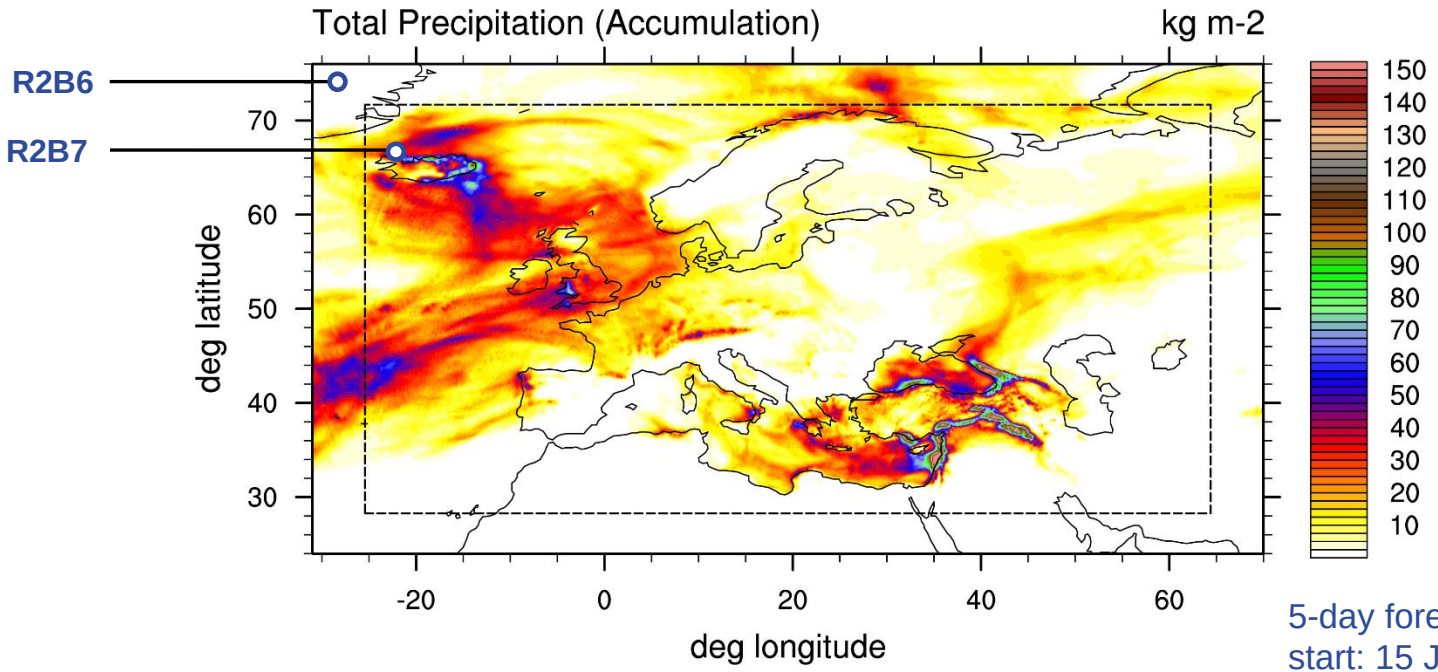
Setup:

- Date: **01-31 Jan 2021**
  one run per day over 180h starting at 00UTC
- Initial conditions: IFS analysis
- Physics: operational DWD settings

3 experiments

- Global with nest: R2B6N7 (40/20km)
- Global low-res: R2B6 (40km)
- Global high-res: R2B7 (20km)

Does Nesting Induce Boundary Artifacts?

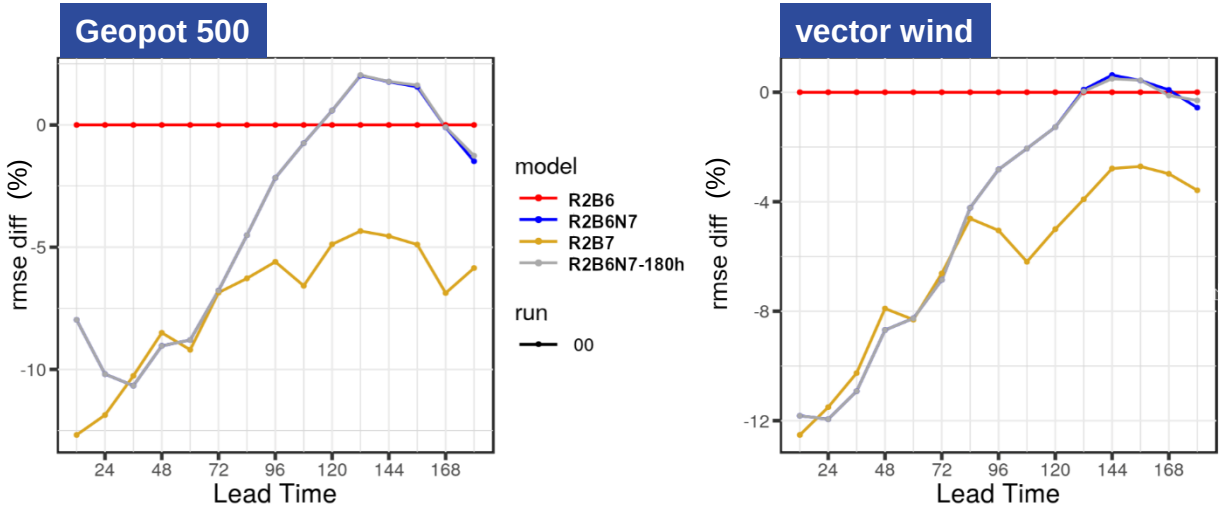


5-day forecast
start: 15 Jan 2021 00UTC

- smooth transition between parent and child solutions
- no significant accumulation of noise

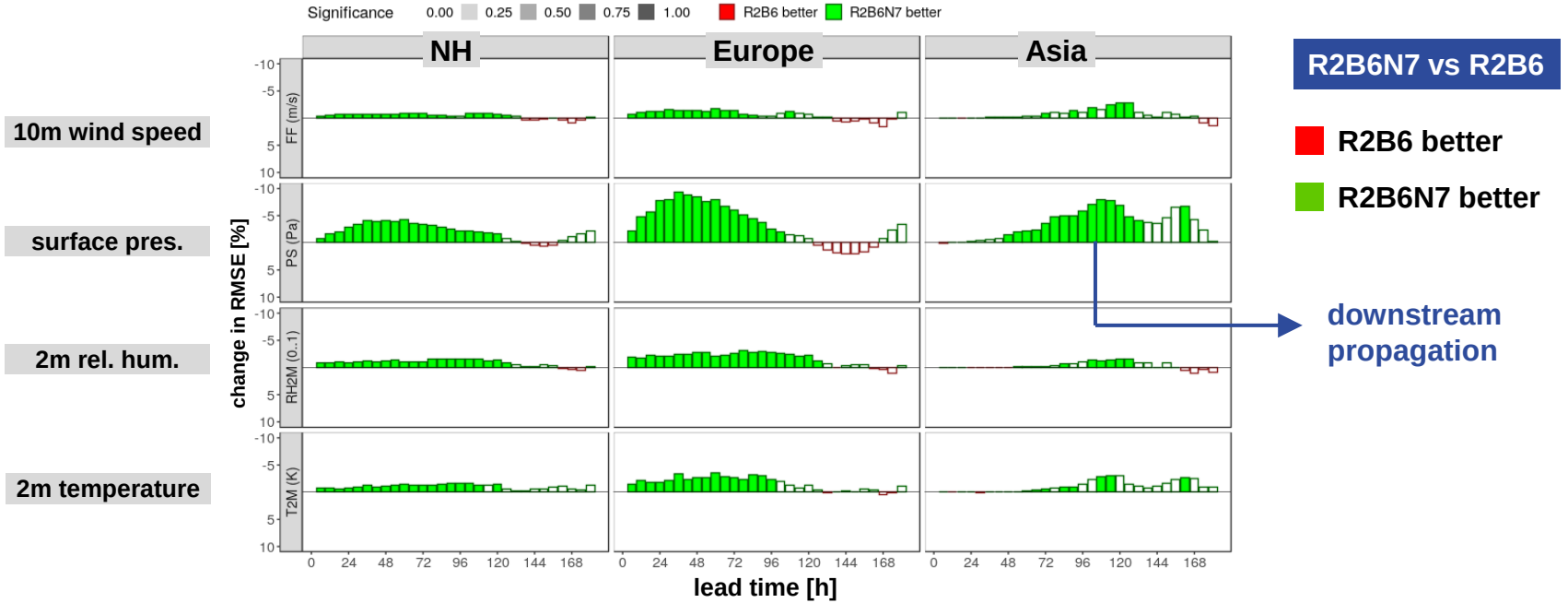
Verification against IFS Analysis for Europe

!! Note that we are exclusively comparing **results for the global domain**.



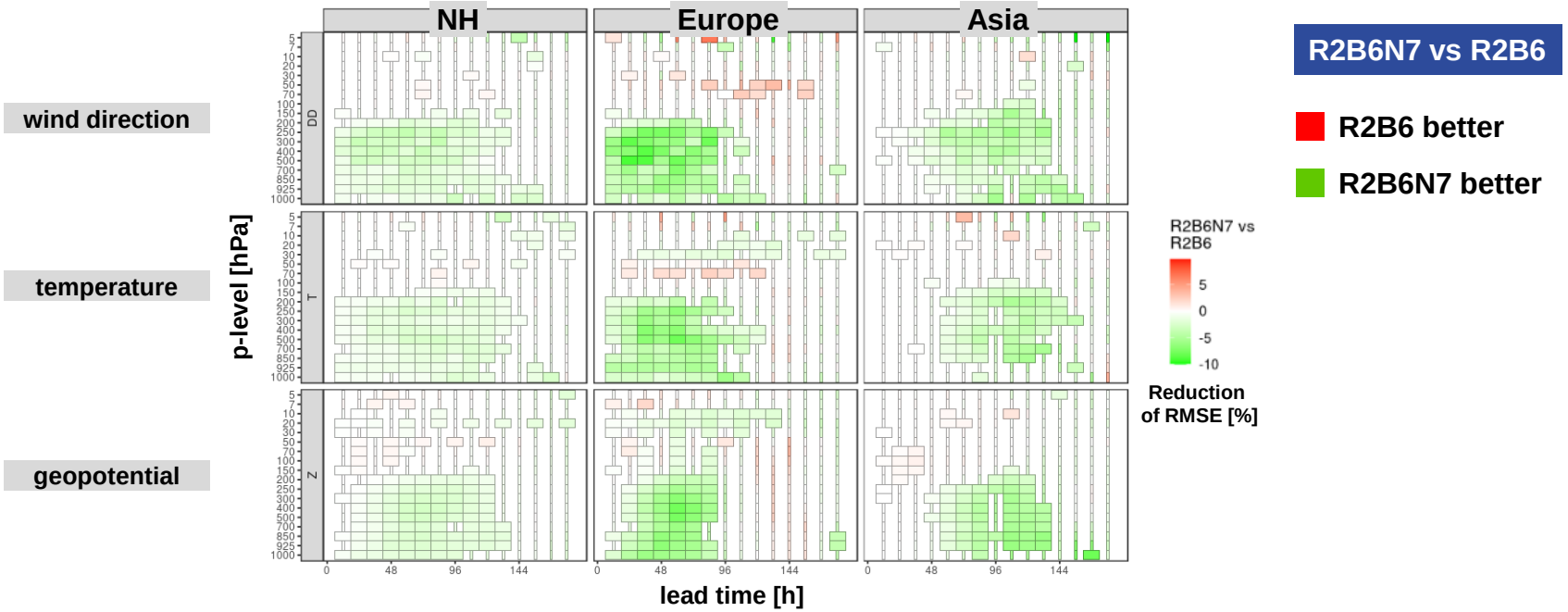
- For lead times < 72 h the improvement due to the nest feedback in R2B6N7 is comparable to that of the global high resolution R2B7 run.
- For lead times > 72 h the improvement in R2B6N7 decreases as the coarse R2B6 boundary data become more and more relevant for the nested domain.

Verification against Synop Stations



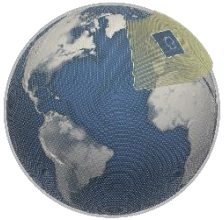
- Europe: beneficial nest impact for lead times < 120h
- Asia: downstream propagation of improvements with a delay of ≈ 72h

Verification against Radiosonde Ascends



- Beneficial nest impact extends throughout the troposphere (and downstream).

Summary (nesting)



- **one-way and two-way hor. nesting** with one or more domains per nesting level available in ICON
- **refinement ratio fixed** to a value of 2
- **vertical nesting:** child domains may have lower top heights
- Full-physics NWP experiments with a nested domain over Europe confirmed that
  - numerical disturbances along nest boundaries are sufficiently small
  - **nest feedback has a significant beneficial impact** on the forecast quality of the global domain
  - beneficial impact is **also observable downstream of the nest location**

Zängl, G., Reinert, D., Prill, F. (2022): *Grid Refinement in ICON v2.6.4*. Geosci. Model Dev. , **15**, 7153-7176
https://doi.org/10.5194/gmd-15-7153-2022

Limited Area Mode (LAM)

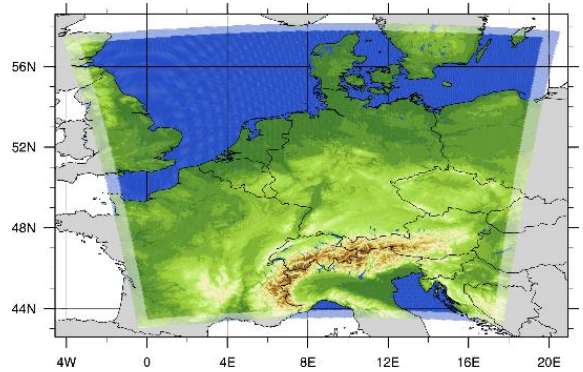
Grid Nesting and Limited Area Mode

Limited Area Mode (LAM)

- Allows the ICON model to be run for an arbitrary section of the earth rather than for the full earth.
- LAM and ICON-global share the same code base.
- **LAM is no separate model**, it is just a specific configuration!
- Switching to LAM ‘in principle’ requires only the activation of the main switch

```
l_limited_area=.TRUE. (grid_nml)
```

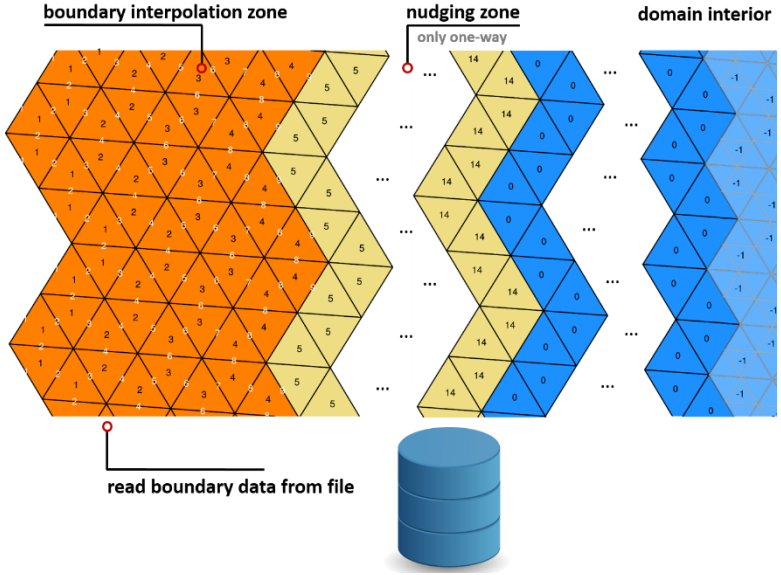
Of course some other adaptions to the namelist settings (tunings) may be necessary as well.



Operational ICON-D2 (2.2km) limited area domain

LAM: a by-product of the nesting implementation

- a limited area domain is technically **equivalent to a one-way nested domain**
  - likewise it has a boundary interpolation zone and nudging zone
- the only **notable difference**:
  boundary data are read from file at regular intervals instead of being interpolated every time step from a parent domain.



Necessary input data

- LAM has one additional input channel for boundary data compared to ICON-global

Boundary data

- can be read asynchronously (recommended)

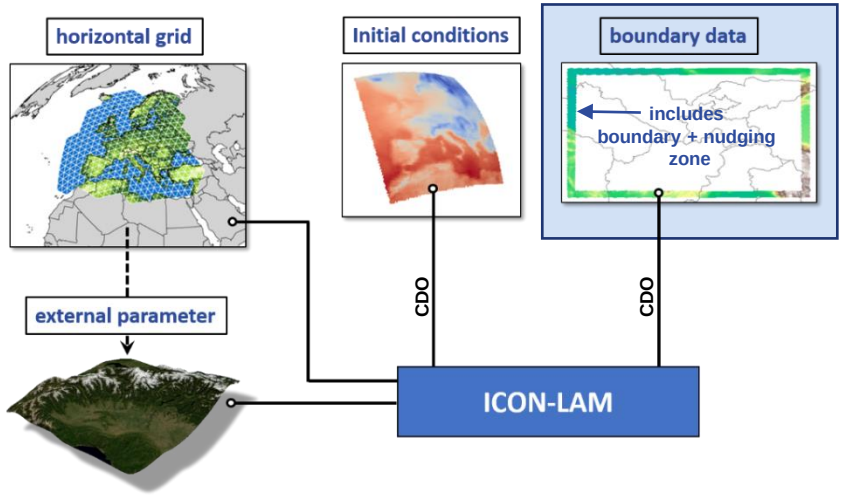
```
num_prefetch_proc = 1 (parallel_nml)
```

- may be provided on the full LAM grid, or an auxiliary boundary grid (see Figure)

- are required for the following (prognostic) variables:

VN, W, THETA_V, DEN, QV, QC, QI, QR, QS, HHL

optional



Necessary input data for ICON-LAM

Boundary grid generation requires DWD ICON Tools

see also talk by Daniel Rieger

Read-in of Boundary Data

see also talk by Daniel Rieger

- based on a decision tree
- several variable sets are supported
- hence, **several driving models are supported**
  (e.g. ICON, COSMO, IFS, …)

Tutorial p.49

Supported variable sets

Set I (e.g. ICON)

{U, V or VN}, W, THETA_V, DEN, QV, QC, QI, QR, QS, HHL

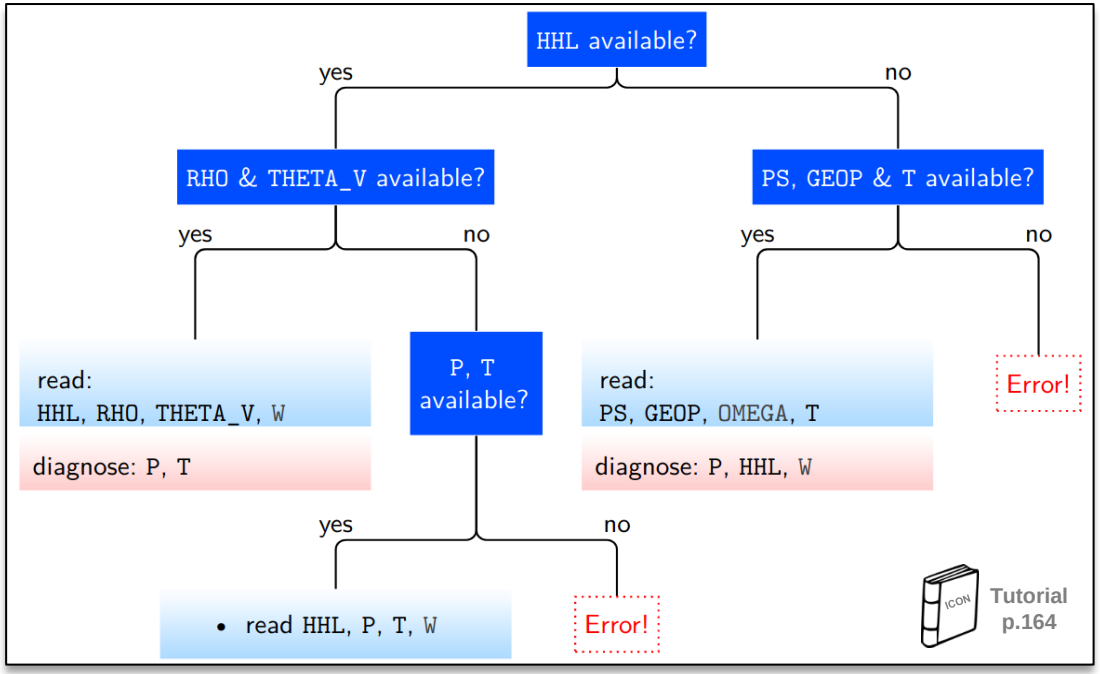
Set II (e.g. COSMO)

U, V, W, T, P, QV, QC, QI, QR, QS, HHL

Set III (e.g. IFS)

U, V, OMEGA, T, LNSP, QV, QC, QI, QR, QS, FI

Decision tree for boundary data read-in



Tutorial p.164

Boundary Nudging

- sponge layer, in which the interior flow is relaxed towards externally specified boundary data.
- prevents spurious reflection of outward propagating waves
- no spectral nudging!

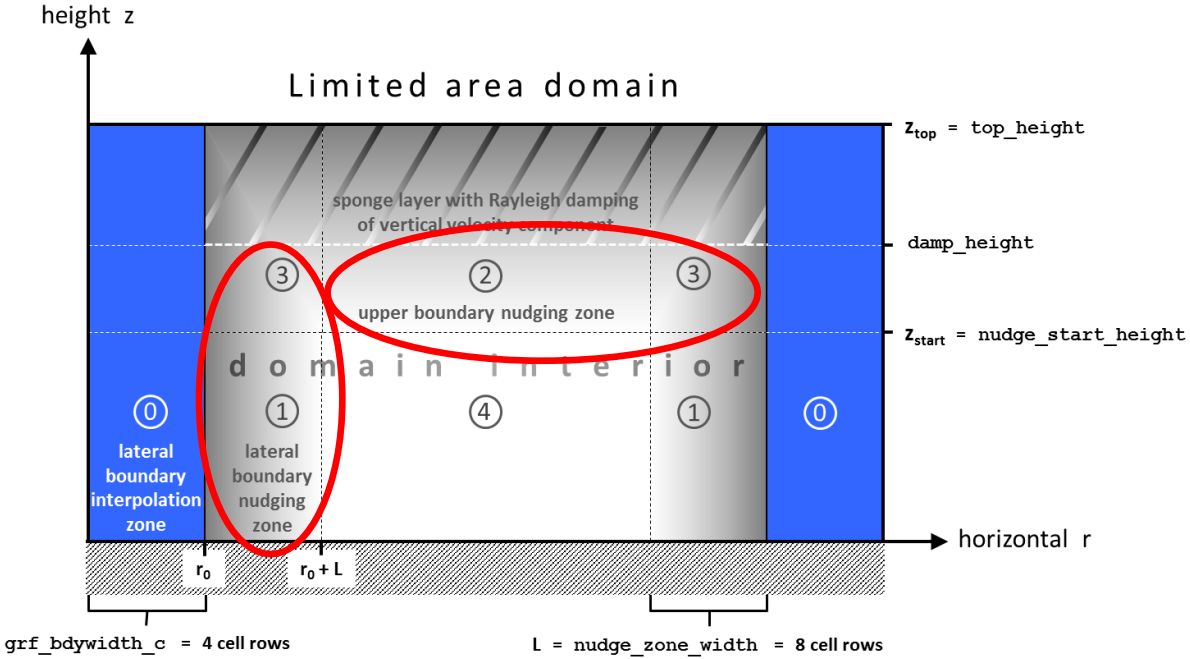
intermediate prog. solution

external boundary data

$$\psi(t) = \psi^*(t) + \alpha_{\text{nudge}} \underbrace{[\psi_{\text{bc}}(t) - \psi^*(t)]}_{=\delta\psi}$$

Davies (1976)

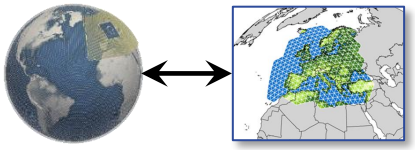
nudging coefficient



Tutorial
Sec. 6.2

LAM vs. Nesting: pros and cons I

When to use LAM ?



LAM:

⊕ **greater flexibility** with regard to **horizontal resolution**

- horizontal resolution can be chosen `freely`
- fixed refinement ratio of 2 does not apply to LAM

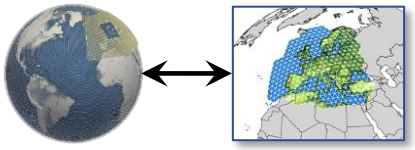
⊕ **greater flexibility** with regard to **vertical resolution**

- number and distribution of vertical layers can be chosen `freely`,
  i.e. no need to match with vertical layers of the driving model
- ICON has built-in vertical interpolation scheme for initial and boundary conditions

⊕ boundary data may be taken from various ‘driving’ models such as ICON, COSMO or IFS

⊕ cheaper compared to global+nest, especially if combined with data assimilation.

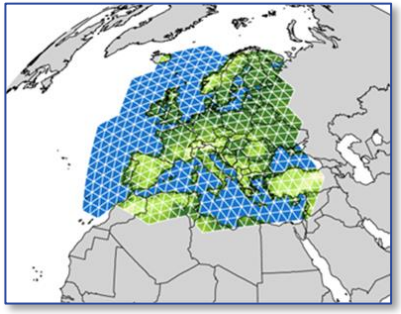
LAM vs. Nesting: pros and cons II



LAM:

- **less frequent lateral boundary updates** compared to 1-way nesting
  (e.g. only every 1h rather than every timestep)
- LAM is technically a little bit more involved in terms of input data preparation:
  - requires an additional pre-processing step (horizontal interpolation with e.g. CDO), in order to generate the boundary data files.
- potential **ill-posedness** of lateral boundary conditions (Davies, 2014)
- possible **inconsistencies with the driving model** (governing equations, numerical formulations, physical parameterizations)
- lack of regional- to global-scale interactions

Summary (LAM)



- Limited Area Mode (LAM) is a **by-product of the grid nesting implementation**
- same code base, same binary as ICON-global
- technically it works like a one-way nested domain (except for boundary forcing)
- provides **greater flexibility** regarding horizontal and vertical resolution compared to one-way nested domains.
- despite deficiencies from a mathematical/theoretical perspective, it has proven successful in various NWP and climate applications.
- used operationally at DWD for convection-permitting NWP over central Europe **(ICON-D2, ICON-D05).**

Thank you for your attention

DWD
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Research and Development
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Literature

Ullrich et al. (2017): *DCMIP2016: a review of non-hydrostatic dynamical core design and intercomparison of participating models*. Geosci. Model Dev., **10**, 4477-4509

Gettelman et al. (2018): *Regional Climate Simulations with the Community Earth System Model*. J. Adv. Model Earth Sy., **10**, 1245-1265

Bindle et al. (2021): *Grid-stretching capability for the GEOS-Chem 13.0.0 atmospheric chemistry model*. Geosci. Model Dev., **14**, 5977-5997

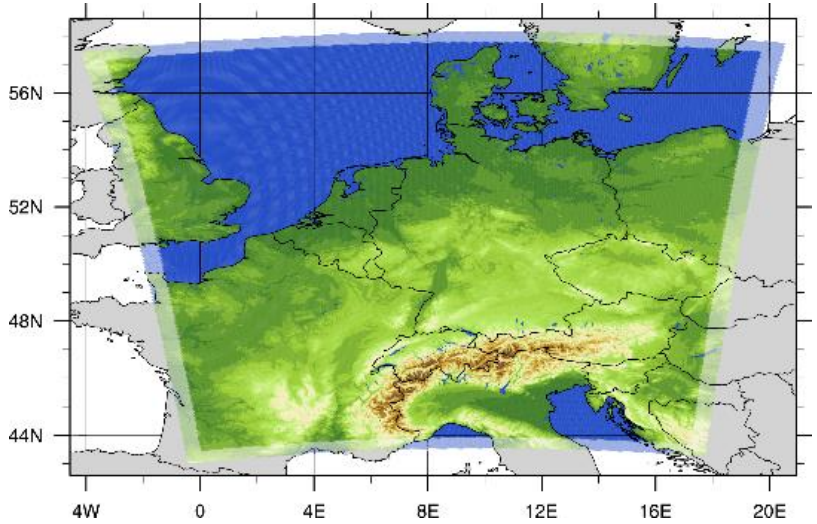
Gao et al. (2019): *Improving AGCM Hurricane Structure with two-way Nesting*. J. Adv. Model Earth Sy., **11**, 278-292

Zängl et al. (2022): *Grid Refinement in ICON v2.6.4*. Geosci. Model Dev., , **15**, 7153-7176 https://doi.org/10.5194/gmd-15-7153-2022

Davies, T. (2014): Lateral boundary conditions for limited area models, Q. J. Roy. Meteor. Soc., **140**, 185-196, https://doi.org/10.1002/qj.2127

Warner, T. T., Peterson, R. A., and Treadon, R. E. (1997): A Tutorial on Lateral Boundary Conditions as a Basic and Potentially Serious Limitation to Regional Numerical Weather Prediction, B. Am. Meteorol. Soc., 78, 2599–2618

Additional Features



- **Limited Area Mode (LAM)**
- may be regarded as a **by-product** of the nesting implementation
  (will be discussed later in this talk)