Domain Nesting in ICON and its Application to AMIP Experiments with Regional Refinement

Vera Maurer[1], Barbara Früh[1], Marco A. Giorgetta[2], Christian Steger[1], Jennifer Brauch[1], Reiner Schnur[3], Günther Zängl[1], Daniel Reinert[4], and Florian Prill[1]

[1]Deutscher Wetterdienst
[2]Max Planck Institute for Meteorology
[3]Max Planck Institute for Meteorology
[4]German Weather Service

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Abstract

The domain nesting of the icosahedral non-hydrostatic (ICON) model has been used operationally at Deutscher Wetterdienst for several years. Now it was also made available for the atmospheric part of the ICON Earth system model. With this new climate configuration, regionally higher resolved simulations without the additional use of a separate regional climate model (RCM) are possible. Simulations were performed for the years 1979-2010 at a global resolution of about 80 km and a subdomain over Europe at 40 km resolution. Two simulations with this setup were evaluated and compared: one with a feedback from the regional subdomain to the global domain (two-way nesting) and one without feedback (one-way nesting). The mean atmospheric state of both simulations on the global scale is only slightly different compared to a reference experiment. However, comparisons to reanalyses show regionally distinct biases. The feedback from the subdomain to the global domain has a similar impact over Europe as a globally higher resolution, indicating a stronger North-Atlantic Oscillation at higher horizontal resolution. Over Europe, the skill is higher in the subdomain than in the global domain, but no systematic advantages can be attributed to the feedback. Artifacts at the lateral boundaries of the regional subdomain, as they are known from RCM simulations, also occur strongly in the simulation without feedback and are eliminated by allowing the feedback. A further reduction of resolution dependency of model physics is supposed to improve particularly the simulation with feedback.

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[1]Deutscher Wetterdienst, Frankfurter Str. 135, 63067 Offenbach
[2]Max-Planck-Institut für Meteorologie, Bundesstr. 53, Hamburg

Key Points:

- A new configuration of a global climate model with domain nesting in the atmospheric part is introduced.
- We demonstrate the functionality of the nesting and find a higher skill for Europe in the nest domain.
- Technical details about the nesting in ICON are given in the appendix.

Corresponding author: Vera Maurer, vera.maurer@dwd.de

Abstract

The domain nesting of the icosahedral non-hydrostatic (ICON) model has been used operationally at Deutscher Wetterdienst for several years. Now it was also made available for the atmospheric part of the ICON Earth system model. With this new climate configuration, regionally higher resolved simulations without the additional use of a separate regional climate model (RCM) are possible. Simulations were performed for the years 1979-2010 at a global resolution of about 80 km and a subdomain over Europe at 40 km resolution. Two simulations with this setup were evaluated and compared: one with a feedback from the regional subdomain to the global domain (two-way nesting) and one without feedback (one-way nesting). The mean atmospheric state of both simulations on the global scale is only slightly different compared to a reference experiment. However, comparisons to reanalyses show regionally distinct biases. The feedback from the subdomain to the global domain has a similar impact over Europe as a globally higher resolution, indicating a stronger North-Atlantic Oscillation at higher horizontal resolution. Over Europe, the skill is higher in the subdomain than in the global domain, but no systematic advantages can be attributed to the feedback. Artefacts at the lateral boundaries of the regional subdomain, as they are known from RCM simulations, also occur strongly in the simulation without feedback and are eliminated by allowing the feedback. A further reduction of resolution dependency of model physics is supposed to improve particularly the simulation with feedback.

Plain Language Summary

For climate simulations, Earth system models (ESM's) are used, consisting of at least an ocean, an atmospheric, and a land model. At the time of writing, most ESM's generate atmospheric data representative for regions of roughly 100 km × 100 km. Additional simulations with higher resolution are performed spanning not the entire globe, but geographically confined regions. Usually, a regional model, which is a separate atmospheric model, is used for these. RCM's typically resolve areas of 10 km × 10 km. In this study, we prepared a new configuration of the atmospheric part of an existing ESM, consisting of a global model and a regional model for Europe running at the same time. The results shown here demonstrate the applicability of this new configuration. One advantage of the new model configuration is an easier handling from a technical point of view. Furthermore, the two models are kept closer to each other, which can improve especially the regional model. We could not yet show this improvement in all aspects, but we discussed the steps necessary to do so. Our model configuration is thus a good compromise between a computationally very expensive high-resolution global ESM and a completely separate regional model.

Keywords

Regional climate model, CORDEX, CMIP, AMIP, Downscaling, Variable resolution modeling

1 Introduction

The use of regional climate models (RCM's) has a long tradition. Giorgi and Mearns (1999) and Rummukainen (2010) give comprehensive reviews. For the Coordinated Regional Downscaling Experiment (CORDEX; e.g. Kotlarski et al. (2014) for EURO-CORDEX, or Dosio et al. (2020) for CORDEX-Africa) being part of the Coupled Model Intercomparison Project (CMIP) of the World Climate Research Program (WCRP), they are essential for the regionalization of global climate projections that had mainly horizontal resolutions on the order of 200 km at the time of CMIP5. At Deutscher Wetterdienst (DWD), RCM simulations are an important basis for climate services with a particular focus on national concerns. For example, the vulnerability of the German transportation infrastructure to impacts of climate change can be investigated in sufficient detail at higher resolutions only (Brienen et al., 2020).

A drawback of using RCM's is the strong dependence of simulation quality on the quality of the driving general circulation model (GCM). In most setups, the atmospheric and the ocean component are interactively coupled in the GCM only, which means that the ocean conditions in the domain of the uncoupled RCM cannot react to the higher resolved atmospheric simulation of the RCM. Moreover, each numerical model produces its own numerical approximation of the real physical state of the atmosphere, and the states of the driving GCM and the RCM can diverge considerably, particularly for domains with large land fraction and integrations extending over several decades. Nudging at or near the model top can be used to reduce a drift of the RCM away from the physical state of the driving GCM in the inner part, apart from the prescribed ocean surface conditions. However, the discrepancy of physical states can cause strong artefacts near the lateral boundaries of the RCM (e.g. Giorgi et al. (1993), or Miguez-Macho et al. (2004)), especially at the outflow region, which cannot be eliminated by commonly used relaxation methods (Leps et al., 2019).

At the same time, the resolution of GCMs is increasing, so that the benefit of RCM's at spatial scales still needing a parametrization of deep convection is slowly starting to decrease. For CMIP6, the resolution in the historical and ScenarioMIP (O'Neill et al., 2016) experiments is around 100 km, which means a twofold increase compared to CMIP5. Moreover, the High Resolution Model Intercomparison Project (HighResMIP) has been defined (Haarsma et al., 2016). Its goal is to provide coupled global model simulations (historical and one scenario) at horizontal scales of at least 50 km in the atmosphere and 0.25° in the ocean. First results show that a higher horizontal resolution of the ocean component or of both the atmospheric and the ocean component can decrease biases in both the ocean and the atmosphere (Gutjahr et al., 2019; Roberts et al., 2020). Demory et al. (2020) show that GCM simulations ("historicals") at 25-50 km horizontal resolution can yield similar scores concerning daily precipitation distribution as 12-50 km CORDEX simulations. However, GCM's at resolutions higher than 50 km in the atmosphere and for time periods typically used in CMIP or CORDEX studies, are still rare owing to the high computational costs.

The idea behind the effort presented here was to prepare a climate configuration of the icosahedral non-hydrostatic (ICON) model, which is capable of domain nesting. The nesting functionality is a general feature of ICON and running operationally with the numerical weather prediction version, with a global domain and a subdomain over Europe (ICON-EU). With a climate configuration of ICON global / ICON-EU, climate simulations with horizontal resolutions of up to 10 km in a subdomain could be achieved at a minimum of additional computing time and storage as well as without any additional pre-processing costs as they are necessary for the preparation of the lateral boundary conditions for traditional RCM simulations.

Using domain nesting, one can take advantage of increased horizontal resolution in a particular region without the enormous increase of computing costs as for a globally higher resolution. Neglecting the computational overhead for the nesting, the nesting is more efficient than a twofold higher resolution globally for subdomain sizes up to a global area fraction of 7/8. Depending on the resolution in the innermost nest, separate RCM simulations can be avoided, but of course, the domain nesting cannot replace the use of RCM's completely. RCM's will be important in CMIP6 for the generation of regional ensembles of climate projections as in CORDEX, where different RCM's are compared using the same forcing provided by a particular GCM or, conversely, simulations performed by an individual RCM using the forcing of different GCM's. Also at convection-permitting scales, RCM's are used, as e.g. in the CORDEX Flagship Pilot Studies (e.g. Coppola et al., 2020).

As to the authors' knowledge, the two-way nesting has been in use for regional models for a long time (e.g. in the mesoscale model MM5, Zhang et al., 1986), but it was not tested before in combination with a GCM. Atmospheric models capable of static grid refinement (i.e. with a uni-grid approach compared to the domain-nesting, which is a multi-grid approach) are for example CAM-SE (Zarzycki et al., 2014), MPAS-A (Skamarock et al., 2012), and the atmospheric part of E3SM (Rasch et al., 2019). They may equally be used for climate projections or forecasts with regionally higher resolved domains (e.g. Tang et al., 2019). An important difference is that physical parametrizations have to be scale-aware in such models while specific settings can be chosen for each domain in ICON. In ICON, however, the horizontal resolution of the subdomain can only be increased by a factor of two with respect to the parent domain, but several domains can be nested into each other.

The aim of this article is to describe the nesting functionality for ICON-A, which is a configuration of the ICON model with ECHAM physics (Stevens et al., 2013), and to show first results of experiments with domain nesting and prescribed ocean surface conditions as well as possible impacts. The experiment with feedback of the subdomain to the global domain in the manner of a two-way nesting is compared to another experiment without feedback, where the subdomain can be regarded as an RCM.

Additionally, a detailed description of the nesting in ICON in general is given in the Appendix.

2 Model Description

2.1 ICON in General

The ICON model was jointly developed by the Max-Planck-Institute for Meteorology (MPI-M) and Deutscher Wetterdienst (DWD). It uses an unstructured triangular grid and a set of non-hydrostatic equations with a Smooth Level Vertical (SLEVE) coordinate (Schär et al., 2002; Leuenberger et al., 2010), which was derived from the z-based terrain-following hybrid Gal-Chen-coordinate (Gal-Chen & Somerville, 1975). Prognostic variables are the edge-normal velocity component v_n, the vertical velocity w, the virtual potential temperature θ_v, the total density of the air mixture $\bar{\rho} = \rho_d + \sum \rho_k$ and the mass fractions $q_k = \rho_k/\bar{\rho}$, with $k \in \{v, c, i, r, s, g\}$. The letters refer to water vapor, cloud water, cloud ice, rain, snow, and graupel, respectively, and d stands for dry air. For ICON-A as described by (Giorgetta et al., 2018), hereafter called G2018, only q_v, q_c, and q_i are prognostic variables, while q_r and q_s are diagnostic. The quantities v_n, w, θ_v, ρ_k and q_k are density-weighted averages (Hesselberg, 1925) describing the mean flow.

The dynamical core and the numerics of the non-hydrostatic ICON model are described by Zängl et al. (2015). Fast physics and advection is called every time step (from now on called large time step) and a dynamical sub-stepping is used to satisfy the stability criterion for the horizontal propagation of sound waves. The ICON model can be used with two different physics packages:

ICON-NWP is partly based on the COSMO model (Baldauf et al., 2011) and its main purpose is numerical weather prediction. Zängl et al. (2015) give an overview of its parametrizations. The large-eddy mode (ICON-LEM, Dipankar et al., 2015) is very similar to ICON-NWP with a Smagorinsky-Lilly-type turbulence parametrization instead of the turbulence scheme imported from the COSMO model (Doms et al., 2018).

ICON-ECHAM physics are similar to those of ECHAM6 (Stevens et al., 2013), apart from necessary technical adaptations. They are used by the atmospheric component of the Earth system model ICON-ESM, which is called *ICON-A* (G2018).

The lower boundary conditions of the atmosphere over land are provided by the JSBACHv4 land model, which is a complete re-write of JSBACHv3.2 to the new infrastructure framework ICON-Land. JSBACHv3 has been the land component of the MPI-M ECHAM and MPIESM models used in many modeling studies over the last decades (Mauritsen et al., 2019). JSBACHv4 currently contains the fast physical, bio-geophysical, and bio-geochemical processes to describe the natural land carbon cycle, disturbances and anthropogenic land cover change, which is a subset of the processes ported from JSBACHv3.2 as described in Reick et al. (2021).

In contrast to the JSBACHv4 configuration used in G2018, a five-layer snow model is applied, and the soil dynamics include freezing water and phase changes between liquid and frozen water (Ekici et al., 2014). In addition, plant productivity by photosynthesis, phenology (leaf area index), roughness lengths for momentum and heat, and visible and near-infrared albedos are computed prognostically on 11 tiles representing subgrid heterogeneity by plant functional types. For this study, transient land cover change was not activated.

The adaptation of ICON-A to horizontal resolutions finer than 10 km, including a prognostic treatment of rain, snow, and graupel, is under development at MPI-M.

Being based on a non-hydrostatic equation system, ICON is very flexible and can be used across a wide range of temporal and spatial scales, from climate scales to weather forecasting and large-eddy simulation scales. The infrastructure of ICON allows for a number of different configurations of the simulation domains: Global and limited-area configurations with or without domain-nesting, and idealized simulations with double periodic boundary conditions are possible. Recently, also a single column mode was developed by Bašták Ďurán et al. (2021). The different physics packages are called from within the time integration loop and use common interfaces for input / output as well as a common code for dynamics, numerics and advection and can therefore all access these configurations of the simulation domains. On the other hand, the physics-dynamics coupling is different for the two physics packages. While all parametrizations are defined either as "fast" or "slow" physics in ICON-NWP (note that slow physics are called with a time step which is even larger than the large time step defined above), allowing for a different splitting of the respective tendencies, no such distinction is made in ICON-A, where technically each process can be treated as fast or slow. However, in practice, ICON-A has been used and tested in a configuration where only the radiation time step was larger.

The different configurations of the simulation domains have been used extensively with ICON-NWP: ICON global / ICON-EU is running operationally at Deutscher Wetterdienst since 2015 at a horizontal resolution of R3B7 (about 13 km, see Prill et al., 2020) globally with a regional subdomain over Europe at a resolution of R3B8 (about 6.5 km). The new convection-permitting regional model for short-range operational weather forecasts of DWD is ICON in limited-area mode (ICON-LAM). Also limited-area simulations with domain nesting are possible (e.g. Klocke et al., 2017). The successor of the regional climate model COSMO-CLM (Rockel et al., 2008) will be ICON-CLM (Pham et al., 2021), which is a configuration of ICON-LAM adapted for climate applications.

In contrast, ICON-A was not used with other configurations than one global domain or for idealized simulations before we started our work. Moreover, tuning was done for the 160 km version only, which is described by G2018.

2.2 Domain Nesting in ICON

The method of the domain nesting was developed at DWD and is described in detail in the Appendix and in Prill et al. (2020). The static mesh refinement in horizontal directions is realized through a multi-grid approach, which means that one or more additional higher resolution (child) domains can be overlaid on a coarser base (parent) domain. This base domain can be a regional or a global domain. Each child domain has a defined parent domain providing lateral boundary conditions, but a parent domain can have several child domains. The child domains can be located in different geographical regions and can also serve as parent domains for further subdomains. Conceptually, the number of nested domains is arbitrary, but of course not all choices would make sense from a physical point of view.

The multi-grid approach in ICON closely resembles traditional two-way nesting as known from many mesoscale models, e.g. MM5 (Grell et al., 1994) or WRF (Skamarock et al., 2019), but differs in the fact that the feedback is based on a Newtonian relaxation approach rather than directly replacing the prognostic fields in the parent domain by up-scaled values from the child domain. It also has to be distinguished from recent uni-grid approaches, where more cells are added to an existing grid in special areas of interest (h-refinement), and where the solver computes a single solution for the whole grid.

The multi-grid approach easily allows for switching domains on or off at runtime, as well as intertwining one-way and two-way nested domains. Two-way as opposed to one-way nesting means that the solution on the child domain is transferred back to the coarser parent domain every parent time step by means of a feedback mechanism.

The refinement ratio between the parent domain and a child domain is fixed to a value of 2, i.e. each parent triangle is split into 4 child triangles. Consistent with the refinement ratio of 2, the time step Δt from parent to child is multiplied by a factor of 0.5. The coupling time step between successive nesting levels is the large (fast physics) time step described in the previous section.

Regarding the implementation of the multi-grid approach, a nested domain can conceptually be split into three areas: The boundary interpolation zone, the nudging zone and the feedback zone (Figure 1). Prognostic computations are restricted to the nudging and the feedback zone. In the *boundary interpolation zone*, necessary lateral boundary data for integrating the model on the nested domain are provided. Boundary conditions are required for the prognostic variables v_n, w, ρ, θ_v, and q_k. By a dedicated boundary update mechanism (see Appendix A11 for details), both the prognostic variables and their tendencies are interpolated from the parent to the child domain.

In the *nudging zone*, which is only active for one-way nesting or in the limited-area mode, prognostic fields of the child domain are nudged towards the model state of the parent domain in order to accommodate possible inconsistencies between the two domains. The nudging is essentially a relaxation of the prognostic variables v_n, ρ, θ_v and q_v towards the lateral boundary data following Davies (1976). More details are given in Appendix A14. For one-way nesting, the nudging is performed at every large time step of the respective child domain.

In the case of two-way nesting, the nudging zone does not exist and the boundary interpolation zone borders on the *feedback zone*. In the feedback zone, the new model state on the parent domain is relaxed towards the updated model state on the child domain every large time step of the parent domain (relaxation-type feedback). By this, the parent and child domain remain closely coupled, and the simulation on the parent domain benefits from the higher-resolution results of the child domain. It is applied to the prognostic variables v_n, w, ρ, θ_v as well as to the prognostic, non-sedimenting mass fractions q_v, q_c, and q_i. See Appendix A13 for further details.

With regard to parallelization for high-performance computing, each domain is distributed onto the whole number of requested processors. This distributed-memory implementation has to be considered when the size of the subdomains and the number of MPI processes is chosen to ensure an adequate scaling, which could be degraded if one subdomain had a considerably smaller number of cells distributed onto a too large number of processors. We refer to Appendix A22 for further details.

In ICON-A as in ICON-NWP, different physical settings can be chosen individually for each domain. For example, radiation can be called more frequently on subdomains or convection can be reduced by stronger entrainment or even be switched off completely.

3 Modifications of the Model Code and Additional Pre-processing

The domain nesting has been available in ICON-NWP for several years. As outlined in Section 2.2, ICON-A accesses the same infrastructure as ICON-NWP and can also access the routines needed for 1-way and 2-way nesting. Therefore, it had mainly to be verified and tested that all physical parametrizations of ICON-A, including JSBACHv4, could consistently interact with these routines.

As mentioned in Section 2.2, nested domains are split into three areas. Grid points lying in the boundary interpolation zone are shifted to the beginning of the index vector and have to be excluded from prognostic computations (see Appendix A22 for details). This treatment was not taken into account in the indexing of several ECHAM physics packages and had to be unified there.

Other code modifications concerned the treatment of the Atmospheric Model Intercomparison Project (AMIP, Gates et al., 1999) forcings for which monthly fields (ozone, sea surface temperature and sea ice fraction) have to be provided for all model domains. Internal interpolation of these fields onto the respective subdomain would also be possible but for the current implementation it was decided to prepare the fields offline for all model domains.

The JSBACHv4 land model already included the capability for domain nesting, but as it had never been tested in this configuration, different modifications had to be done there, too.

Vertical nesting is only implemented for ICON-NWP. For the future, vertical nesting would be a desirable feature in ICON-A as it could save additional computing time, but the lack of vertical nesting should not have any impact on the model results.

The generation of all necessary input data for the subdomains is not yet possible with the EXTPAR software (Asensio et al., 2020) as for ICON-NWP, which interpolates all topography-, vegetation-, and soil-specific data, land-sea masks and also climatological fields as for example aerosol distributions, and performs a consistency check of all generated data. Additionally, it is not clear if it would be feasible to include all monthly fields which are necessary for AMIP simulations. Thus an alternative pre-processing had to be applied for subdomain extraction and interpolation, based on a combination of the Climate Data Operators (Schulzweida, 2020) and on internal DWD software. This software was also used for the generation of the subdomain grids.

4 Experiment Setup

Two AMIP simulations were performed with ICON-A and domain nesting, one with and one without feedback. The global domains (hereafter referred to as *GLO-2way* and as *GLO-1way* for the simulations with two- and one-way nesting, respectively) had a horizontal resolution of approximately 80 km (ICON resolution of R2B5, see G2018 for further details), and a regional subdomain of approximately 40 km over Europe shown in Figure 2. The subdomain of GLO-2way is referred to as *REG-2way*. Accordingly, *REG-1way* is the subdomain of GLO-1way. REG-1way is comparable to an RCM simulation without spectral nudging apart from the increased update frequency of the lateral boundary conditions (see Section 2.2 for more details). GLO-1way in turn is comparable to a global 80 km simulation without any subdomain. Additionally, an experiment at a globally higher resolution of about 40 km as in the subdomain (hereafter called *GLO-hires*) was performed for 1979 only to give an estimate of the impact of the horizontal resolution at the global scale.

In the vertical, 90 levels up to the model top at 83 km were used for all simulations and domains. The subdomain was chosen with the same rotated pole as the CORDEX domain for Europe, but with a larger extent so that a second nest at 20 km resolution can be included in future applications.

Default parameters for the physics, as defined in the ICON-A version tuned by G2018, were used apart from $csecfrl = 5 \cdot 10^{-5}\,\mathrm{kg\,kg^{-1}}$ (default: $5 \cdot 10^{-6}\,\mathrm{kg\,kg^{-1}}$), controlling the minimum water mass mixing ratio in mixed phase clouds, and $crs = 0.925$ (default: 0.968), which is the critical relative humidity at the surface used for the determination of the cloud cover profile. These values were motivated from tuning experiments performed at MPI-M with ICON-A at 160 km horizontal resolution, generating globally a higher total cloud cover, a higher liquid water and ice content, and lower atmospheric as well as surface temperatures over the northern hemisphere continents compared to the reference experiment with the default settings.

The time step was set to 6 minutes with 5 dynamical substeps. This time step is comparably small but after a recent bug fix, a larger value can be chosen for future experiments, which can also save computation time. The time step of 3 minutes in the subdomain is determined internally. Radiation was called hourly in both domains, apart from the radiative heating, which is called every large time step of the respective simulation domain. The cloud microphysics are called every 6 minutes in all simulation domains. This was necessary as the cloud scheme showed a strong time-step dependency, which partly contributed to large precipitation differences between GLO-2way and REG-2way. The drawback of the adaptation of the cloud microphysics time step in all simulation domains was that a second subdomain of 20 km horizontal resolution was not possible: A time step of 6 minutes for the cloud microphysics, which is a fast physical process (i.e. in general, it should be called every large time step), in combination with the large time step of 90 seconds results in model instabilities.

All other physical parametrizations except radiation were called at every large time step of the respective simulation domain. Standard forcings from the AMIP experiment of ICON-A were used: Monthly mean fields of sea surface temperature, sea ice fraction, and ozone, the Max Planck Institute aerosol climatology with the simple plume parametrization (MACv2-SP) for transient natural tropospheric, stratospheric, and anthropogenic aerosols, transient greenhouse gases, and the spectral solar irradiance. G2018 give more details about these forcings.

In comparison to the experiments described by G2018, we used a higher global horizontal and vertical resolution (80 km with 90 levels instead of 160 km with 47 levels). Moreover, the configuration of the land model was different: G2018 used only one general vegetated tile and no frozen soil water, while we used 11 tiles (see Section 2.1). Finally, corrected external parameters were used, as an error in the pre-processing of topography data used for the subgrid-scale orography scheme had been detected. The simulations were performed for the period 1979-2010 and evaluated for the 30-year period 1981-2010, which is one of the past climate reference periods defined by the World Meteorological Organization.

5 Evaluation

For the evaluation of the two ICON simulations with nesting, both the global and the subdomains were analyzed and compared. For the global domains, mean fields were computed for the years of 1981-2010 and compared to the ERA-Interim reanalysis of the European Centre for Medium-Range Weather Forecasts (Dee et al., 2011). For the calculation of the mean differences and the root mean square error (RMSE), ERA-Interim was regridded to the native ICON grid, but the plots shown here were prepared by interpolating both fields onto a common regular latitude-longitude grid. The ranges of values from the tuning experiments described by G2018 are given to estimate the impact of the different experiment setup compared to G2018 (see Section 4).

As mentioned in Section 4, the global fields were also compared to those from GLO-hires for the first year of the AMIP simulation (1979). The mean fields for 1979 differ from the mean fields for 1981-2010 mainly in their smoothness (not shown), therefore the comparison between the differences for the two periods should be valid. For the comparisons, annually averaged fields of GLO-hires were interpolated to the horizontal resolution of GLO-2way and GLO-1way (ICON native grid of R2B5).

For the subdomains, the E-OBS dataset version 17.0 (Haylock et al., 2008) and time series of cloud cover from CRU (Jones & Harris, 2008) were used. The model output was re-gridded to the E-OBS grid at $0.25° \times 0.25°$ horizontal resolution.

The main focus of the evaluation was on the comparison of the two simulations in order to describe the impact of the two-way nesting in comparison to one-way nesting.

5.1 Global Domains

For the global domain GLO-2way, the difference of the 1981-2010 mean field for 2 m temperature to ERA-Interim reveals a strong positive bias over the northern hemisphere continents in summer (Figure 2a). Over large parts of Eurasia, the mean bias is larger than 5 K. Compared to GLO-1way, 2 m temperature in summer is higher over Central Asia (Figure 2b), which means that the positive temperature bias is stronger in GLO-2way. This bias can also be seen in global ICON-A simulations at lower horizontal resolution and was reduced by the parameter settings mentioned before. Almost no differences between GLO-2way and GLO-1way appear over the oceans, as expected for an AMIP experiment with prescribed sea surface temperatures.

In winter, the positive bias with respect to ERA-Interim is still existent over parts of Northern America and East Asia (Figure 2c). It is warmer in GLO-2way than in GLO-1way over Northern America, but cooler over Asia (Figure 2d). The region with higher 2 m temperatures over Northern America in GLO-2way only partly coincides with that of the positive bias with respect to ERA-Interim. Over Europe, there is a negative temperature bias in GLO-2way, which is stronger than in GLO-1way in Scandinavia (negative differences in Figure 2d), and weaker over Central Europe (positive differences in Figure 2d). Overall, the 2 m temperature bias with respect to ERA-Interim is slightly smaller in GLO-2way, i.e. when the feedback from the subdomain is active (Table 1). Especially in winter, the impact of the feedback can be seen over Northern America as strongly as over Europe, where the subdomain is located. Furthermore, the effect of the feedback on the global domain is essentially restricted to the Northern hemisphere, again where the subdomain is located.

For other variables, global mean values for GLO-1way and GLO-2way are given in Table 1. Mean precipitation of 2.74 mm d^{-1} and 2.73 mm d^{-1}, respectively, is only marginally higher than the estimate of the Global Precipitation Climatology Project (GPCP) Monthly Analysis Version 2.3 (Adler et al., 2018) of 2.69 mm d^{-1}. The difference between GLO-1way and GLO-2way is negligible. For the vertically integrated water vapor, the mean difference is also small, and both values are slightly higher than the ERA-Interim mean, which is 24.28 kg m^{-2}. The standard deviation of the difference field to ERA-Interim is higher for GLO-2way. The vertically integrated cloud water (87 g m^{-2} and 85 g m^{-2}) is too high compared to observations, which are in the range of 50-80 g m^{-2} (Mauritsen et al., 2012). All experiments in G2018 show values below 65 g m^{-2}. Higher values here can be related to the choice of parameters, which resulted in a smaller positive temperature bias, but also in more cloud water. Too high values are similarly found for cloud ice (below 30 g m^{-2} in G2018 and 34 g m^{-2} / 33 g m^{-2} here). Total cloud cover is on the lower end compared to the experiments shown by G2018 (0.63-0.645 %), but acceptable with a global mean value larger than 60 % (Mauritsen et al., 2012). The short- and longwave components of the top-of-atmosphere radiation budget are both low but within the range given by G2018. Their sum has a small positive value in agreement with the satellite-based observational average of the Clouds and the Earth's Radiant Energy System (CERES) project shown in G2018.

Concerning the geographical distribution of differences between mean fields for GLO-2way and GLO-1way, further systematic differences are shown for 1981-2010 mean sea level pressure (psl, Figure 3a), total precipitation (Figure 3b), total cloud cover (Figure 3c) and integrated water vapor (Figure 3d). The pattern of the psl-difference field indicates a stronger North-Atlantic Oscillation (NAO) in GLO-2way than in GLO-1way. This pattern is much more pronounced in winter and very weak in summer (not shown). The precipitation difference over the Northern Atlantic indicates a shift of precipitation in GLO-2way towards the north compared to GLO-1way, in agreement with a stronger NAO. As for mean sea level pressure, this difference pattern is much more pronounced in winter. For 2 m temperature, higher values as expected for a stronger NAO occur over mid-Europe in winter (Figure 2d).

Difference fields of GLO-2way and GLO-1way for cloud cover (Figure 3c), integrated water vapor (Figure 3d), and also for vertically integrated cloud water (not shown), show different patterns: Mainly in the region of the subdomain, i.e. in the region where the feedback is active, cloud cover and integrated water vapor/cloud water are reduced strongly in GLO-2way compared to GLO-1way. It is assumed that this is an effect of the increased resolution in the subdomain, which can be seen in GLO-2way due to the feedback. Lower values in GLO-2way are similarly obvious at the eastern boundary of REG-2way for water vapor. This reduction of water mass tracers and of cloud cover in GLO-2way compared to GLO-1way can be related to the stronger NAO index, shifting precipitation towards the north and favouring drought conditions in Central Asia. Only the negative wintertime difference of 2 m temperature in Central Asia is not in agreement with this assumption.

The difference fields of GLO-2way and GLO-1way for 1979 (Figure 4a-c) show similar patterns as the difference fields of GLO-hires and GLO-1way (Figure 4), which means that the feedback from REG-2way to GLO-2way has generally the same influence as a globally higher horizontal resolution. Cloud cover and cloud water in mid-latitudes in GLO-hires are indeed also lower in the region of REG-2way (Figures 4 e, f), confirming the assumption that decreased water vapor, cloud water and cloud cover in GLO-2way in the region of the subdomain is an effect of the horizontal resolution. More detailed analyses of cloud processes would be necessary to understand these resolution-dependent differences. It can only be assumed that the dependency of microphysics on cloud cover becomes critical at 40 km resolution. For the fields shown in Figure 4 (2 m temperature, vertically integrated cloud water and total cloud cover) and for other fields (not shown), the differences between GLO-1way and GLO-hires are larger than between GLO-1way and GLO-2way. Nonetheless, many patterns as for example positive 2 m temperature differences over Europe, east of Greenland, in the eastern US, parts of Central Asia, and even in the southern hemisphere (e.g. Brasil) are similar in location and strength (Figures 4a and d). This comparison also holds for negative temperature differences as for example over Canada and northern Africa, confirming that the influence of the feedback is also seen outside of the subdomain, i.e. outside of the feedback region. Thus, increased horizontal resolution within a confined geographical region naturally has a smaller influence all over the globe than a globally higher horizontal resolution, but still it exists in regions remote to REG-2way, which means that a propagation of local differences via the global atmospheric circulation takes place.

5.2 Comparison of the Simulation Results for the Subdomain and the Global Domain

The global mean precipitation agrees well with the GPCP estimate (see Section 5.1 and Table 1), but over Europe (20°W – 40°E, 30 – 70°N, i.e. parts of the Northern Atlantic and of Northern Africa are included), precipitation is in all domains by 25 % to almost 40 % lower than the GPCP mean value of 2.20 $\mathrm{mm\,d^{-1}}$ (mean value calculated for the years of 1981-2010). With 1.34 $\mathrm{mm\,d^{-1}}$, the lowest value of all domains can be found for GLO-2way. The difference of REG-2way to GLO-2way of 0.24 $\mathrm{mm\,d^{-1}}$ (with large-scale precipitation contributing 0.22 $\mathrm{mm\,d^{-1}}$) was already reduced by more than 30 % - this value was calculated for the area-average for the first year of the AMIP simulation - by an adaptation of the calling frequency of the cloud microphysics, as already mentioned in Section 4. Concerning its geographical distribution, the mean precipitation in GLO-2way (Figure 5a) shows a maximum in the western part of the Northern Atlantic, geographically in agreement with GPCP, but with a stronger decrease towards the east (Figure 5b). Also over European land, mean precipitation is smaller than shown by GPCP. In REG-2way (Figure 5c), precipitation is slightly higher than in GLO-2way (difference shown in Figure 5e), as already obvious from the area-averaged values. The maximum precipitation difference of REG-2way to GLO-2way of up to 0.6 $\mathrm{mm\,d^{-1}}$ occurs over the Northern Atlantic at about 30°W. Still, values in REG-2way are lower than those of GPCP.

The difference of REG-1way to GLO-1way (Figure 5f), i.e. between the regional and the global domain of the simulation without feedback, is also mainly positive and in the same range of values. Thus, the tendency for higher precipitation sums in the subdomain exists in both simulations. On the other hand, the difference pattern is different in the simulation without feedback with a maximum more to the east. The contribution of the convective precipitation difference to the total precipitation difference is negligible with feedback and larger without feedback (not shown). Area-averaged values for convective precipitation confirm a larger difference between GLO-1way and REG-1way ($0.1\,\mathrm{mm\,d^{-1}}$) than for GLO-2way and REG-2way ($0.02\,\mathrm{mm\,d^{-1}}$).

The difference of REG-1way to REG-2way (Figure 5d) is largely similar to the difference of GLO-1way to GLO-2way (Figure 3b), both displaying a northward shift of precipitation over the Northern Atlantic, in relation with the more intense NAO pattern. In the difference field of the two subdomains, artefacts occur in the boundary interpolation zone and in the nudging zone. As explained in Section 4, diagnostic fields are not filled within the boundary interpolation zone. Artefacts in the nudging zone, especially in the outflow region, are well known from RCM and also from shorter-scale limited-area simulations. The lateral boundaries are usually excluded as soon as scores are calculated or if more in-depth comparisons with other datasets are performed.

For other fields, differences between the regional and the global domain are naturally smaller in the simulation with feedback than in the one without feedback (Figure 6), as the relaxation draws the fields of the prognostic variables in the global domain towards those in the regional one. Differences of REG-1way - GLO-1way indicate that the subdomain is cooler than the global domain over Europe apart from Spain, with a maximum over Scandinavia of up to $-3\,\mathrm{K}$ near the land surface (2 m temperature, Figure 6a). The vertically integrated water vapor is lower in REG-1way over most parts of the subdomain (Figure 6b), with a confined region of positive differences in the northeastern part of the domain. Vertically integrated cloud water is larger in REG-1way to the west of Scandinavia and lower over Europe (apart from Spain and the Mediterranean region) and over Russia. Total cloud cover is also lower in REG-1way than in GLO-1way to the west of Scandinavia (Figure 6d), geographically in agreement with the region of higher convective precipitation (not shown). The difference fields of two global simulations for 1979 at the respective horizontal resolution (Figures 4d, e, f) show roughly similar patterns as those for REG-1way and GLO-1way (Figures 6a, b, d), apart for 2 m temperature. Therefore, it can be assumed that the differences between REG-1way and GLO-1way are mainly generated by a different behaviour of the physical parametrizations at different horizontal resolutions. A reduction of these differences is desirable.

5.3 Comparison with Observations for Europe

For 2 m temperature, the difference fields to E-OBS all show a negative temperature bias over UK and parts of France and Germany, and a positive bias in all other regions (Figure 7). Apart from GLO-1way (Figure 7a), the negative bias is also present in Scandinavia. It is strongest in REG-1way and has the opposite sign for GLO-1way, in agreement with the strong negative temperature difference there for REG-1way - GLO-1way (Figure 6a). Otherwise, the difference fields to E-OBS present a positive bias of the 2 m temperature, with a maximum in the southeast of the displayed domain. The positive bias over Scandinavia in GLO-1way is mainly a less negative bias in winter, which can be deduced from the global difference fields (Figures 2b and d) showing higher temperatures for GLO-1way than for GLO-2way, especially in winter. In agreement with small 2 m temperature differences between REG-2way and GLO-2way, bias maps are very similar for GLO-2way and REG-2way (Figures 7b and d). Most obvious improvement of REG-2way over GLO-2way is present in mountainous regions, as in in the Alps, the Pyrenees, or the Apennines in Europe, or the Atlas mountains in Africa. Apart from the benefits of resolution in mountainous regions, no clear preference can be attributed to either of the shown domains when comparing the bias fields for the temporally averaged 2 m temperature, but REG-2way has the smallest negative biases and smaller positive biases than GLO-2way.

The mean annual cycle of 2 m temperature is slightly too pronounced compared to E-OBS (Figure 8a) for area averages of the region shown in Figure 6, with the positive bias in summer being stronger than the negative one in winter. Differences between the simulation domains are small compared to the difference to E-OBS. For the 2 m daily minimum temperature (Figure 8c), the positive bias in summer is similar while there is no negative bias in winter, with a larger spread in-between the domains. For 2 m maximum temperature (Figure 8e), the warm bias in summer is smaller than for 2 m daily mean and minimum temperature, but the wintertime cold bias is stronger, indicating too low maximum temperatures. From this it follows that the annual 2 m temperature cycle over land is too large over Europe, but that the diurnal cycle is too small, especially in winter.

The RMSE for the mean monthly fields with respect to E-OBS mainly shows lower 2 m temperature deviations for GLO-1way and REG-1way in summer and lower deviations for GLO-2way and REG-2way in winter (Figures 8b, d, and f). For all domains, RMSE is higher in summer and winter than in spring and autumn, which also confirms the over-pronounced annual cycle. Still, the RMSE is larger than 0 in the months when the area-averages are equal to the E-OBS average (especially in spring and autumn), because the difference field is never completely equal to 0. In most months, the subdomains display slightly lower RMSE's than their respective parent domains. Differences in RMSE tend to be larger between GLO-1way and REG-1way than between GLO-2way and REG-2way, in agreement with the larger mean difference fields. Large RMSE values for REG-1way in January to March are caused by strongest cold biases there in the regions around the Baltic Sea (not shown).

The negative precipitation bias that was already detected when comparing with GPCP precipitation (Figure 5), is obvious throughout the whole year (Figure 8g). As for temperature, the RMSE for precipitation is lower for GLO-1way and REG-1way in summer and lower for GLO-2way and REG-2way in winter, but weaker in January to May (Figure 8h). Lower RMSE's for the subdomains are clearer than for 2 m temperature, especially for REG-2way.

For cloud cover, the annual cycle is too pronounced (Figure 8i), as for the 2 m temperature. In GLO-2way, the values of area-averaged cloud cover are the lowest ones, in agreement with the negative difference between GLO-2way and GLO-1way. The RMSE is the highest in summer (or in the months of May to September, Figure 8j), when the low values are most distinct. In contrast, GLO-1way displays the highest values in most months, most distinct when all domains have a positive bias, with the highest RMSE of all domains in October to February.

Overall, neither of the simulations or domains has systematically lowest or highest RMSE's. Main improvement of the simulation with feedback compared to the simulation without feedback is visible in winter, while the simulation without feedback shows lower RMSE's in summer. Largest reduction of the RMSE in the subdomain of the simulation with feedback compared to its parent domain occurs for precipitation throughout the whole year and for cloud cover for the months from April to September. However, the simulation without feedback has still a lower RMSE for these months in both domains. Especially for precipitation, this can be explained by a smaller negative bias.

6 Summary and Conclusions

The nesting functionality, which is used operationally with ICON-NWP at DWD since 2015, was now also made available for ICON-A. As ICON-A is the atmospheric component of the coupled ESM, this model configuration can allow for simultaneous global and regional climate projections at low additional computing and storage costs. With this article, we document the current status and the capabilities of the nesting functionality in ICON-A as well as its limitations. Additionally, the added value of higher horizontal resolution in the subdomain over Europe was investigated. Two AMIP simulations with one-way and two-way nesting, respectively, were performed for the years of 1979-2014 and evaluated for 1981-2010 at a global horizontal resolution of about 80 km and of 40 km in the subdomain over Europe. For two-way nesting, a relaxation-based feedback from the subdomain to the global domain is active. An additional purely global simulation at the same horizontal resolution as in the subdomain (40 km) was evaluated for the first year (1979). The evaluations were done (1) for the global domain, (2) for the global and the regional domains in comparison and (3) for Europe including a more detailed verification against observations. The main results are that

(1) there is a clear near-surface warm bias over northern hemisphere continents in summer, which is stronger over Eurasia - apart from Scandinavia - in the simulation with feedback. Over Europe, there is a cold bias in winter. Global mean values of vertically integrated cloud water and cloud ice are too high compared to Giorgetta et al. (2018) as well as to the range of different observations, but they are realistic for precipitation, cloud cover, the radiation budget and precipitable water. Thus, the global ICON-A simulations could and should still be tuned to provide more realistic results, especially if the geographical distribution of the biases is considered, but the global mean biases are overall within an acceptable range, both with and without the feedback from a higher-resolved subdomain.
The difference fields between the two simulations indicate a stronger NAO for the simulation with two-way nesting. Accordingly, precipitation is shifted towards the north over the Northern Atlantic, and central-European winters are warmer in the simulation with two-way nesting compared to the one with one-way nesting. Difference fields between the global 40-km simulation and the horizontally lower resolved global domain of the simulation with one-way nesting are structurally similar, but have larger amplitudes. The two-way nesting therefore has a similar, but attenuated influence on the atmospheric fields as a globally higher horizontal resolution.

(2) the mean precipitation is too low over Europe for all domains, with the lowest value in the respective part of the global domain with feedback. For both simulations, precipitation is higher in the subdomain than in the respective global domain. The differences between the two subdomains are mainly similar to the differences between the two global domains. They also hint at a stronger NAO. Accordingly, the differences between the global domain and the subdomain are very small for two-way nesting and larger for one-way nesting. Artefacts in the boundary interpolation zone occur strongly in the simulation with one-way nesting. They are eliminated by the two-way nesting.

(3) the verification against the E-OBS data set shows a cold bias in the north-western part of Europe and a warm bias in the south-east in all domains. In the subdomains, the biases are smaller than in the global domains especially in mountainous regions as the Alps, the Pyrenees or the Apennines. The annual cycle of 2 m temperature is too pronounced while the diurnal cycle is too small. In most months, the RMSE is slightly lower in the subdomain compared to the respective global domain. For the two simulations with nesting in comparison, one or the other shows lower RMSE's, depending on the season. The precipitation bias is negative throughout the whole year, as already shown by the comparison to GPCP. Concerning all RMSE's of all considered variables, none of the simulations or domains is clearly the best.

In summary, it was shown that large differences appear between the forcing, i.e. the global simulation, and the subdomain when no feedback is used. Mean biases for the subdomain and the respective part of the global domain are mainly similar, but in some regions even the sign of the bias changed. This means that, even with the same physics and only a factor of two in horizontal resolution between the global and the regional model, the mean atmospheric state in a subdomain can differ from the one produced by the global simulation. The large horizontal extent of the subdomain probably contributes to these differences. Considering similarities to the difference fields of two global simulations at the respective horizontal resolutions, these differences can be attributed to the different behaviour of the physical parametrizations at different horizontal resolutions. They are not generated by the general approach of regional climate modeling as discussed by Giorgi and Mearns (1999).

To test if the feedback to the global domain as a part of the 2-way nesting, which partly alters the atmospheric fields, results in an adequate modification of these fields, they were compared with the global simulation at the higher horizontal resolution. Comprehensive similarities could be found in the geographical patterns. Thus, the feedback mechanism is also consistent for long time scales. It was shown that the NAO is stronger at higher resolution as well as with 2-way nesting. If it can be confirmed that the NAO is also more realistic at higher resolution, this finding means that a higher-resolved subdomain has the potential to improve climate forecasts and projections for the Euro-Atlantic region.

On the other hand, large differences between global ICON-A simulations at different horizontal resolution are not desirable. Hertwig et al. (2015) showed that errors of ECHAM6, which is the predecessor of ICON-A, were decreasing with horizontal resolution and only minimal retuning. They compared experiments of roughly 200 km, 150 km, and 50 km in an AMIP setup, and could infer a larger improvement in the extra-tropics than in the tropics. Crueger et al. (2018) find that ICON-A, in contrast to ECHAM6, produces a different climate at higher horizontal resolution (approximately 40 km) compared to a lower resolution (approximately 160 km), with increased mean errors at higher resolution. One reason that ICON-A does presently not show such a clear improvement with horizontal resolution as ECHAM6 could be that resolution-dependent tuning parameters, influencing for example the activity of the convection scheme, were implemented in ECHAM, but not in ICON-A. It was not within the scope of this study to analyze all differences arising from simulations at different horizontal resolution. Nevertheless, it can be assumed that the verification scores of a simulation in a similar setup as the one introduced here with a regional subdomain over Europe and two-way nesting would be improved if the global simulations with ICON-A were optimized at both resolutions. This optimization could be done either by namelist tuning as shown by Giorgetta et al. (2018) or by more specific work on individual parts of the physics package such that 1) biases compared to ERA-Interim and 2) resolution differences are minimized. Possible approaches are a more in-depth analysis of atmospheric circulations patterns or of land-surface atmosphere feedbacks, which strongly influence near-surface temperatures.

To sum it up, the new setup of the atmospheric part of an Earth system model with a flexible horizontal grid-refinement was shown to be fully functional and its possible applications for climate forecasts or projections are promising. At the same time, more optimization will be needed to enhance its absolute added value.

A full ESM can be achieved by coupling both simulation domains to one global ocean model (ICON-O, Korn, 2017) via the YAC coupler by providing the same ICON-O fields to both atmospheric domains and by returning atmospheric variables from the nested domain in this particular region and from the global domain otherwise. Of course, a retuning of the full ICON-ESM would be necessary then.

Appendix A Implementation of the Grid Nesting in ICON

A1 Parent-Child Coupling

This section describes the exchange of information between a single parent and child domain. Recall the different zones illustrated in Figure 1, i.e. the boundary interpolation zone, nudging zone, and feedback zone. Let the model state on the parent and child domain be denoted by $\mathcal{M}_p^n$ and $\mathcal{M}_c^n$, respectively, where n specifies the time step index.

A11 Lateral Boundary Update: Parent → Child

The boundary update mechanism provides the child domain with up-to-date lateral boundary conditions for the prognostic variables v_n, w, ρ, θ_v, q_k. In order to avoid that parent-to-child interpolated values of ρ enter the solution of the mass continuity equation, the above set of variables is extended by the horizontal mass flux ρv_n. This will allow for parent-child mass flux consistency, as described below.

In general, the boundary update works as follows: Let ψ_p^n, ψ_p^{n+1} denote any of the above variables on the parent domain at time steps n and $n+1$, respectively. Once the model state on the parent domain $\mathcal{M}_p$ has been updated from n to $n+1$, the time tendency

$$\frac{\partial \psi_p}{\partial t} = \frac{\psi_p^{n+1} - \psi_p^n}{\Delta t_p}$$

is diagnosed. Both, the field ψ_p^n at time level n and the tendency $\frac{\partial \psi_p}{\partial t}$ are then interpolated (downscaled) from the parent grid cells/edges to the corresponding cells/edges of the child's boundary zone, which has a fixed width of 4 cell rows (see Figure 1). With $\mathcal{I}_{p\to c}$ denoting the interpolation operator, we get

$$\begin{aligned} \psi_c^n &= \mathcal{I}_{p\to c}\left(\psi_p^n\right) \\ \frac{\partial \psi_c}{\partial t} &= \mathcal{I}_{p\to c}\left(\frac{\partial \psi_p}{\partial t}\right) \end{aligned}$$

The interpolated tendencies are generally needed in order to provide the lateral boundary conditions at the right time levels, since two integration steps are necessary on the child domain in order to reach the model state $\mathcal{M}_c^{n+1}$, with each step consisting of (typically 5) dynamics sub-steps. E.g. for the first and second (large) integration step on the child domain the boundary conditions read ψ_c^n and $\psi_c^n + 0.5\,\Delta t_p \partial\psi/\partial t|_c$, respectively.

Regarding the interpolation operator $\mathcal{I}_{p\to c}$ we distinguish between cell based variables (i.e. scalars) and edge-based variables (v_n and ρv_n). For cell based variables a 2D horizontal gradient is reconstructed at the parent cell center by first computing edge-normal gradients at edge midpoints, followed by a 9-point reconstruction of the 2D gradient at the cell center based on radial basis functions (RBF Narcowich & Ward, 1994). The interpolated value at the jth child cell center is then calculated as

$$\psi_{c_j} = \psi_p + \nabla\psi_p \cdot \boldsymbol{d}(p, c_j)\,, \qquad j \in \{1\ldots 4\}\,, \tag{A1}$$

with $\nabla\psi_p$ denoting the horizontal gradient at the parent cell center, and $\boldsymbol{d}(p, c_j)$ the distance vector between the parent and jth child cell center. The same operator is applied to cell based tendencies.

To prevent excessive over- and undershoots of ψ_{c_j} in the vicinity of strong gradients, a limiter for $\nabla\psi_p$ is implemented. It ensures that

$$\frac{1}{\beta}\psi_{p,\mathtt{min}} < \psi_{c_j} < \beta\psi_{p,\mathtt{max}} \qquad \forall\, j \in \{1\ldots 4\}$$

on all four child points, where $\psi_{p,\mathtt{min}}$ and $\psi_{p,\mathtt{max}}$ denote the minimum and maximum of ψ_p, respectively, on the above-mentioned reconstruction stencil plus the local cell center, and $\beta = 1.05$ is a tuning parameter.

Regarding the interpolation of edge-based variables (i.e. the edge-normal vector components v_n and ρv_n), we distinguish between *outer child edges* that coincide with the edges of the parent cell, and *inner child edges* (see Figure A1a).

Edge-normal vector components at the inner child edges are reconstructed by means of a direct RBF reconstruction using the five-point stencil indicated in Figure A1a. For a given inner child edge the stencil comprises the edges of the corresponding parent cell, and the two edges of the neighboring parent cells that (approximately) share the orientation of the inner child edge.

For the outer child edges a more elaborate reconstruction is applied, in order to assure that the mass flux across a parent edge equals the sum of the mass fluxes across the corresponding child edges. We start with an RBF reconstruction of the 2D vector of the respective variable at the triangle vertices, using the six (five at pentagon points) edge points adjacent to a vertex (see Figure A1b).

The edge-normal vector component ϕ at the child edge is then computed as

$$\phi_{c_e} = \phi_p + \nabla_t \phi_p \cdot \boldsymbol{d}(p, c_e)\,, \qquad e \in \{1, 2\}\,,$$

with $\boldsymbol{d}(p, c_e)$ denoting the distance vector between the parent and child edge midpoints for a given parent edge, and $\nabla_t \phi_p$ denoting the gradient of the edge-normal vector component ϕ_p tangent to the parent edge. The latter is computed by projecting the 2D vectors at the two vertices of an edge onto the edge-normal direction and taking the centered difference. Since by construction $\boldsymbol{d}(p, c_1) = -\boldsymbol{d}(p, c_2)$ holds on the ICON grid, the above mentioned mass flux consistency is ensured.

It is noted that attempts to use higher-order polynomial interpolation methods, which are the standard in mesoscale models with regular quadrilateral grids, were unsuccessful on the triangular ICON grid, because the ensuing equation system led to the inversion of nearly singular matrices.

In order to minimize interpolation errors, the following modifications from the above interpolation procedure are applied: For the thermodynamic variables ρ and θ_v perturbations from the reference state (Zängl et al., 2015) rather than the full values are interpolated, in order to reduce interpolation errors above steep orography.

Rather than interpolating v_n and its time tendencies, only the time tendencies are interpolated, and then used to update v_n at child level at every dynamics time step. The wind field v_n itself is interpolated only once during the initialization of the child domain. This methodology has been chosen because the comparatively inaccurate interpolation to the interior child edges tends to induce small-scale noise in v_n. To suppress the remaining noise arising from the interpolation of the time tendency, a second-order diffusion operator is applied in the inner half of the boundary interpolation zone on v_n, and the default fourth-order diffusion applied in the prognostic part of the model domain (see Zängl et al., 2015) is enhanced in the five grid rows adjacent to the interpolation zone. For the other prognostic variables, no special filtering is applied near nest boundaries. In the case of one-way nesting, the second-order velocity diffusion is extended into the nudging zone of the nested domain, replacing the enhanced fourth-order diffusion. More details on the nudging zone are given in Section A14.

For the horizontal mass flux ρv_n, the time average over the dynamic sub-steps, which is passed to the tracer transport scheme in order to achieve mass consistency, is interpolated instead of time level n. Using the mass flux time tendency that is interpolated as well, the related time shift is corrected for when applying the boundary mass fluxes at child level. In the nested domain, the interpolated mass fluxes valid for the current time step are then prescribed at the interface edges separating the boundary interpolation zone from the prognostic part of the nested domain. Due to the flux-form scheme used for solving the continuity equation (see Zängl et al., 2015), this implies that the interpolated values of ρ do not enter into any prognostic computations in the dynamical core. They are needed, however, for some computations in the transport scheme. Moreover, no mass fluxes at interior child edges are used, so that the non-conservative interpolation method used for those edges does not affect the model's conservation properties. For θ_v and the tracer variables q_k, the values at the edges are reconstructed in the usual manner (see Zängl et al., 2015) and then multiplied with the interpolated mass fluxes before computing the flux divergences.

A12 Vertical Nesting

The vertical nesting option allows to set model top heights individually for each domain, with the constraints that the child domain height is lower or at most equal to the parent domain height, and that the child domain extends into heights where the coordinate surfaces are flat. This allows, for instance, a global domain extending into the mesosphere to be combined with a child domain that extends only up to the lower stratosphere (see Figure A2).

However, a vertical refinement in the sense that the vertical resolution in the child domain may differ from that in the parent domain is not available. One possible workaround might be to repeat the model run with the desired vertical resolution in limited area mode.

In the ICON model, the top height for child domains can be specified by means of a namelist parameter. If vertical nesting is activated, boundary conditions need to be provided at the vertical interface level, i.e. the uppermost half level of the nested domain, for all prognostic variables. Appropriate boundary conditions are crucial in order to prevent vertically propagating sound and gravity waves from being spuriously reflected at the nest interface. Boundary conditions for v_n, w, θ_v, ρ, q_k as well as the vertical mass flux ρw are specified as follows:

For w, θ_v, ρ and ρw the full fields at the nest interface level are interpolated from the parent to the child grid, using the same RBF based interpolation method (A1) as for the lateral boundary conditions. Rather than interpolating instantaneous values as for the lateral boundaries, w, θ_v, ρ, and ρw are averaged over all dynamics substeps constituting a large time step, in order to filter the oscillations related to vertically propagating sound waves. Hence, for $\psi \in \{w, \theta_v, \rho, \rho w\}$ the boundary condition reads

$$\psi_c = \mathcal{I}_{p\to c}\left(\frac{1}{\texttt{nsubs}}\sum_{s=1}^{\texttt{nsubs}} \psi_p^{n+s/\texttt{nsubs}}\right),$$

with `nsubs` denoting the number of dynamics substeps (usually $\texttt{nsubs} = 5$). In the current implementation, the boundary values are kept constant during the two large time steps and related dynamics substeps on the child domain.

A slightly different approach is taken for v_n, which turned out to be beneficial in order to reduce the magnitude of the horizontal interpolation errors. The differences between the nest interface level and the next half level below (denoted as Δv_n in the following) are interpolated rather than the full field. After interpolating $\Delta v_{n,p}$ to the child domain (using again the same methods as for the lateral boundary conditions) they are added to $v_{n,c}$ at the second interface level ($k = 2$) on the child domain, in order to obtain the upper boundary condition, i.e.

$$v_{n,c}(k=1) = v_{n,c}(k=2) + \mathcal{I}_{p\to c}\left(\frac{1}{2}\left(\Delta v_{n,p}^{n} + \Delta v_{n,p}^{n+1}\right)\right).$$

Since Δv_n is less strongly affected by sound waves, only an average between the first and the last dynamics substep is taken prior to the interpolation.

For the tracer variables we refrain from directly interpolating the partial mass fluxes $(\rho w q_k)_p$, in order to ensure tracer- and air mass consistency. Instead, we make use of the already interpolated mass flux $(\rho w)_c$ and multiply it with proper mass fractions. On the parent domain the required mass fractions are derived by taking the ratio of the vertical tracer mass flux at the nest interface calculated in the vertical transport scheme $(\rho w q_k)_p$ and the available mass flux $(\rho w)_p$. The mass fractions are then interpolated to the child domain, using method (A1). Hence, the flux boundary conditions for arbitrary tracer fields q_k read

$$(\rho w q_k)_c = (\rho w)_c \mathcal{I}_{p\to c} \left(\frac{(\rho w q_k)_p}{(\rho w)_p} \right) .$$

A13 Feedback: Child → Parent

If two-way nesting is activated, the model state $\mathcal{M}_p^{n+1}$ on the parent domain is relaxed towards the updated model state $\mathcal{M}_c^{n+1}$ on the child domain at every fast physics time step. In the following we will refer to this as *relaxation-type feedback*. It is restricted to the prognostic variables v_n, w, θ_v, ρ plus specific humidity q_v and the specific contents of cloud water q_c and cloud ice q_i. Precipitating hydrometeors are excluded because recommended relaxation times (see below) are longer than their typical falling times. Surface variables are excluded as well because they can easily adjust during runtime and a proper treatment of feedback along land-cover inhomogeneities (e.g. coastlines) would be complicated and probably computationally expensive.

Let ψ denote any of the above mentioned variables. Conceptually, the feedback mechanism is based on the following three basic steps:

(1) *Upscaling*: The updated field ψ_c^{n+1} is interpolated (upscaled) from the child domain to the parent domain. The upscaling operators for cell based and edge based variables will be denoted by $\mathcal{I}_{c\to p}$ and $\mathcal{I}_{ce\to p}$, respectively.
(2) *Increment computation*: The difference between the solution on the parent domain ψ_p^{n+1} and the upscaled solution $\mathcal{I}_{c\to p}(\psi_c^{n+1})$ is computed.
(3) *Relaxation*: The solution on the parent domain is relaxed towards the solution on the child domain. The relaxation is proportional to the increment computed in Step 2.

For cell based variables the upscaling consists of a modified barycentric interpolation from the four child cells to the corresponding parent cell:

$$\mathcal{I}_{c\to p}(\psi_c) = \sum\nolimits_{j=1}^{4} \alpha_j \psi_{c_j} .$$

The weights α_j are derived from the following constraints (A2)–(A4). First of all, a desirable property for the value interpolation is that it reproduces constant fields, i.e. the weights are normalized:

$$\sum\nolimits_{j=1}^{4} \alpha_j = 1 . \tag{A2}$$

Moreover, the interpolation is linear: With the four child cell circumcenters $\boldsymbol{x}_j$ $(j = 1, \ldots, 4)$, and $\boldsymbol{x}_p$ denoting the parent cell center, i.e. the interpolation target, we set

$$\sum\nolimits_{j=1}^{4} \alpha_j (\boldsymbol{x}_j - \boldsymbol{x}_p) = 0 . \tag{A3}$$

To motivate this constraint, consider the special case of equilateral triangles in which the center point of the inner child cell $\boldsymbol{x}_1$ coincides with the parent center such that the term $(\boldsymbol{x_1} - \boldsymbol{x_p})$ vanishes. Equation (A3) now defines a barycentric interpolation within the triangle spanned by the mass points of the three outer child cells $\{c_2, c_3, c_4\}$ (see Figure A1a), where the weights $\{\alpha_2, \alpha_3, \alpha_4\}$ represent the barycentric coordinates.

Of course, the contribution of the point $\boldsymbol{x}_1$ closest to the interpolation target is of particular importance. Therefore, the underdetermined system of equations (A2), (A3) is closed with a final constraint which reads as

$$\alpha_1 = \frac{a_{c_1}}{a_p} , \tag{A4}$$

where a_{c_1} and a_p denote the inner child and parent cell areas, respectively. In other words, the inner child cell c_1 containing the parent cell circumcenter is given a pre-defined weight corresponding to its fractional area coverage. This can be interpreted as a conservation constraint for the special case of a very localized signal at the mass point of the inner child cell.

In summary, this method can be regarded as a *modified* barycentric interpolation for the mass points $\{\boldsymbol{x}_2, \boldsymbol{x}_3, \boldsymbol{x}_4\}$, and which accounts for $\boldsymbol{x}_1$ as an additional fourth source point. A more stringent barycentric interpolation would require an additional triangulation based on the child mass points.

For velocity points, a simple arithmetic average of the two child edges lying on the parent edge is taken.

$$\mathcal{I}_{ce\to p}(v_{n,e}) = \frac{1}{2}\left[v_{n,e_{\text{child 1}}} + v_{n,e_{\text{child 2}}}\right]$$

We note that the operator $\mathcal{I}_{c\to p}$ is not strictly mass conserving and that strict mass conservation would require some means of area-weighted aggregation from the child cells to the parent cells, which is available as an option. The problem with such methods on the ICON grid is related to the fact that the mass points lie in the circumcenter rather than the barycenter of the triangular cells. Using an area-weighted aggregation from the child cells to the parent cells, would map linear horizontal gradients on the child grid into a checkerboard noise pattern between upward and downward oriented triangles on the parent grid.

Another difficulty that was encountered in the context of mass conservation is related to the fact that the density decreases roughly exponentially with height. In the presence of orography, the atmospheric mass resolved on the model grid therefore increases with decreasing mesh size, assuming the usual area-weighted aggregation of the orographic raw data to the model grid. Feeding back ρ is thus intrinsically non-conservative. To keep the related errors small and non-systematic, and to generally reduce the numerical errors over steep mountains, perturbations from the reference state are used for upscaling ρ and θ_v to the parent grid. A closer investigation of the related conservation errors revealed that the differences between bilinear and area-weighted averaging are (with real orography) unimportant compared to the resolution-dependent conservation error.

When combining the above mentioned steps, the feedback mechanism for ρ can be cast into the following form:

$$\rho_p^* = \rho_p^{n+1} + \frac{\Delta t_p}{\tau_{fb}}\left(\mathcal{I}_{c\to p}(\rho_c^{n+1} - \Delta\rho_{corr}) - \rho_p^{n+1}\right) \tag{A5}$$

Here ρ_p^{n+1} denotes the density in the parent cell, which has already been updated by dynamics and physics. The superscript “$*$“ indicates the final solution, which includes the increment due to feedback. Δt_p is the fast physics time step on the parent domain, and τ_{fb} is a user-defined relaxation time scale which has a default value of $\tau_{fb} = 10800\,\text{s}$. This value is independent of the relaxed field. It aims to exclude small scale transient features from the feedback, but to fully capture synoptic-scale features.

Finally note that the upscaled density includes the correction term $\Delta\rho_{corr}$ which has been introduced in order to account for differences in the vertical position of the child and parent cell circumcenters. At locations with noticeable orography, cell circumcenter heights at parent cells can differ significantly from those at child cells. If this is not taken into account, the feedback process will introduce a non-negligible bias in the parent domain's mass field. The correction term is given by

$$\Delta\rho_{corr} = \left(1.05 - 0.005\,\mathcal{I}_{c\to p}(\theta'^{\,n+1}_{v,c})\right)\,\Delta\rho_{ref,p}\,,$$

with the parent-child difference in the reference density field

$$\Delta\rho_{ref,p} = \mathcal{I}_{c\to p}(\rho_{ref,c}) - \rho_{ref,p}\,,$$

and the potential temperature perturbation $\theta'^{\,n+1}_{v,c} = \theta^{n+1}_{v,c} - \theta_{v\,ref,c}$. The term $\Delta\rho_{ref,p}$ is purely a function of the parent-child height difference and can be regarded as a first order correction term. In order to minimize the remaining mass drift, the empirically determined factor $(1.05 - 0.005\,\mathcal{I}_{c\to p}(\theta'^{\,n+1}_{v}))$ was added, which introduces an additional temperature dependency. Note that the factor 0.005 is close to near surface values of $\frac{\partial\rho}{\partial\theta}$ which can be derived from the equation of state. We further note that a possibly more accurate and less ad hoc approach would require a conservative remapping step in the vertical, prior to the horizontal upscaling.

Care must be taken to ensure that the feedback process retains tracer and air mass consistency. To this end, feedback is not implemented for tracer mass fractions directly, but for partial densities. In accordance with the implementation for ρ, we get

$$(\rho q_k)^*_p = (\rho q_k)^{n+1}_p + \frac{\Delta t_p}{\tau_{fb}}\left[\mathcal{I}_{c\to p}((\rho^{n+1}_c - \Delta\rho_{corr})q^{n+1}_{k,c}) - (\rho q_k)^{n+1}_p\right] \tag{A6}$$

Mass fractions are re-diagnosed thereafter:

$$q_{k,p} = \frac{(\rho q_k)^*_p}{\rho^*_p}$$

When summing Eq. (A6) over all partial densities, Eq. (A5) for the total density is recovered.

A very similar approach is used for θ_v. As for ρ, only the increment of θ_v is upscaled from the child- to the parent domain and added to the parent reference profile $\theta_{v\,ref,p}$.

$$\theta^*_{v,p} = \theta^{n+1}_{v,p} + \frac{\Delta t_p}{\tau_{fb}}\left(\mathcal{I}_{c\to p}(\theta'^{\,n+1}_{v,c}) + \theta_{v\,ref,p} - \theta^{n+1}_{v,p}\right)$$

The same approach is taken for w, however the full field is upscaled.

$$w^* = w^{n+1} + \frac{\Delta t_p}{\tau_{fb}}\left(\mathcal{I}_{c\to p}(w^{n+1}_c) - w^{n+1}_p\right)$$

In the case of v_n some numerical diffusion is added to the resulting feedback increment in order to damp small-scale noise.

$$v^*_{n,p} = v^{n+1}_{n,p} + \frac{\Delta t_p}{\tau_{fb}}\left(\Delta v_{n,p} + K\,\nabla^2\left(\Delta v_{n,p}\right)\right)\,,$$

with the feedback increment

$$\Delta v_{n,p} = \mathcal{I}_{ce\to p}(v^{n+1}_{n,c}) - v^{n+1}_{n,p}\,,$$

and the diffusion coefficient $K = \frac{1}{12}\frac{a_{p,e}}{\Delta t_p}$, where $a_{p,e}$ is the area of the quadrilateral spanned by the vertices and centers adjacent to the parent's edge.

A14 Lateral Nudging

If the feedback is turned off, i.e. if one-way nesting is chosen, a nudging of the prognostic child grid variables towards the corresponding parent grid values is needed near the lateral nest boundaries in order to accommodate possible inconsistencies between the two grids, particularly near the outflow boundary. Because lateral boundaries are in general not straight lines on the unstructured ICON grid, attempts to make an explicit distinction between inflow and outflow boundaries (e.g. by prescribing v_n at inflow boundaries only) were not successful.

To compute the nudging tendencies, the child grid variables are first upscaled to the parent grid in the same way as for the feedback, followed by taking the differences between the parent-grid variables and the upscaled child-grid variables. The differences are then interpolated to the child grid using the same methods as for the lateral boundary conditions (see above). The relaxation uses weighting factors decreasing exponentially from the inner margin of the boundary interpolation zone towards the interior of the model domain. The nudging zone width and the relaxation time scale can be adjusted by the user. Default values are 8 cell rows for the width and $0.02\,\Delta\tau$ (dynamics time step) for the relaxation time scale. The relaxation weights decay with a default e-folding width of 2 cell rows. As already mentioned, a second-order diffusion on v_n is used near the lateral nest boundaries in order to suppress small-scale noise.

A2 Implementation Aspects

A21 Recursive Algorithm

So far, we have focused on the coupling of an individual parent and child domain. The coupling of multiple and possibly repeatedly nested domains requires a well conceived processing sequence, whose basics will be described in the following.

Figure A3 provides a common example where a global domain is combined with two repeatedly nested domains (two-way). The global domain is schematically depicted at the bottom, whereas the nested domains are vertically staggered on top of it. The red and blue regions show the boundary interpolation zones and feedback zones of the individual domains, respectively. The integration time step on the global domain is denoted by Δt. It is automatically reduced by a factor of 2 when moving to the next child grid level.

The processing sequence for the integration of all domains from time step n to $n+1$ is shown in the flowchart at the lower left of Figure A3. The domains are ordered top down. Open and filled black dots show model states without and with feedback increments, black arrows indicate time integration, and red and blue arrows indicate lateral boundary data interpolation and feedback, respectively.

From an abstract point of view, the flow control of ICON's hierarchical nesting scheme is handled by a recursive subroutine that cascades from the global domain down to the deepest nesting level and calls the time stepping and the physics parameterizations for each domain in basically the same way as for the global domain. The basic processing sequence is as follows:

(1) A single integration step with Δt is performed on the global domain which, results in an updated model state $\mathcal{M}_p^{n+1}$, indicated by an open black circle.
(2) Boundary data are interpolated from the global domain to the first nested domain (red arrow), followed by an integration step on nested domain 1 over the time interval $\Delta t/2$.
(3) As there exists another nested domain within nest 1, boundary fields based on the model state $\mathcal{M}_{c1}^{n+1/2}$ are interpolated to the second nested domain. Afterwards, the model is integrated on nested domain 2 over two times the time interval $\Delta t/4$, resulting in the model state $\mathcal{M}_{c2}^{n+1/2}$.
(4) Feedback is performed from nest 2 back to nest 1 (blue arrow), which results in an updated model state $\mathcal{M}_{c1}^{n+1/2*}$ on nested domain 1 (black filled dot). Then, on nested domain 1 the model is again integrated in time to reach model state $\mathcal{M}_{c1}^{n+1}$.
(5) This is followed by a second lateral boundary data interpolation from nest 1 to nest 2 based on $\mathcal{M}_{c1}^{n+1}$. Nest 2 is integrated in time again, to reach its state $\mathcal{M}_{c2}^{n+1}$.
(6) As a final step, feedback is performed from nest 2 to nest 1, followed by feedback from nest 1 to the global domain.

A22 Distributed-Memory Parallelization

Several measures are taken in order to optimize the computational efficiency of the nesting implementation.

In the model grids, grid points lying at or near the lateral boundary of a nested domain are shifted to the beginning of the index vector, ordered by their distance from the lateral boundary. This allows excluding boundary points from prognostic computations accessing non-existing neighbor points without masking operations. In the present implementation, the four outer cell rows constituting the boundary interpolation zone (see Figure 1), and the adjacent fifth one participate in the reordering.

The reordering makes use of the grid meta-data field `refin_c_ctrl` which counts the distance from the lateral boundary in units of cell rows (see Figure 1). Correspondingly, there are integer flag arrays for edges and vertices replicating the distance information from the lateral boundary. This distance information is extended to a larger number of grid rows in order to provide the geometric information needed for lateral boundary nudging. Moreover, the flag arrays signify grid points overlapping with a child domain, including a distinction between boundary interpolation points and interior overlap points.

Regarding distributed-memory (MPI) parallelization, the general strategy adopted in ICON is to distribute all model domains among all compute processors. As this implies that child grid points are in general owned by a different processor than the corresponding parent grid point, an intermediate layer having the resolution of the parent grid but the domain decomposition of the child grid is inserted in order to accommodate the data exchange required for boundary interpolation and feedback.

To reduce the amount of MPI communication for complex nested configurations, multiple nested domains at the same nesting level can be merged into one logical domain which is then not geometrically contiguous. This needs to be done during the grid generation process by indicating a list of domains. The lateral boundary points belonging to all components of the merged domain are then collected at the beginning of the index vector. For all prognostic calculations, the multiple domains are treated as a single logical entity, and just the output files may be split according to the geometrically contiguous basic domains. As one-way and two-way nesting cannot be mixed within one logical domain, there may still be two logical domains on a given nest level.

To further optimize the amount of MPI communication, a so-called processor splitting is available that allows for executing several nested domains concurrently on processor subsets whose size can be determined by the user in order to minimize the ensuing load imbalance. This option is currently restricted to the step from the global domain to the first nesting level in order to keep the technical complexity at a managable level.

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the text and in the cited literature, respectively. ERA-interim data sets are available from ECMWF (http://apps.ecmwf.int/datasets/data/interim-full-daily/).

References

Adler, R. F., Sapiano, M. R. P., Huffman, G. J., Wang, J.-J., Gu, G., Bolvin, D., ... Shin, D.-B. (2018). The global precipitation climatology project (GPCP) monthly analysis (new version 2.3) and a review of 2017 global precipitation. *Atmosphere*, *9*(4). doi: 10.3390/atmos9040138

Asensio, H., Messmer, M., Lüthi, D., Osterried, K., & Jucker, J. (2020). *External parameters for numerical weather prediction and climate application EXTPAR v5_4. User and implementation guide.* Retrieved from `http://cosmo-model.org/content/support/software/ethz/EXTPAR_user_and_implementation_manual.pdf`

Baldauf, M., Seifert, A., Förstner, J., Majewski, D., Raschendorfer, M., & Reinhardt, T. (2011). Operational convective-scale numerical weather prediction with the COSMO model: description and sensitivities. *Monthly Weather Review*, *139*(12), 3887–3905.

Bašták Ďurán, I., Köhler, M., Eichhorn-Müller, A., Maurer, V., Schmidli, J., Schomburg, A., ... Dewani, N. (2021). The ICON single column mode. *Atmosphere*, *submitted*, xx.

Brienen, S., Walter, A., Brendel, C., Fleischer, C., Ganske, A., Haller, M., ... Stanley, K. (2020). *Klimawandelbedingte Änderungen in Atmosphäre und Hydrosphäre: Schlussbericht des Schwerpunktthemas Szenarienbildung (SP-101) im Themenfeld 1 des BMVI-Expertennetzwerks* (Digitale Publikationsreihe im BMVI-Expertennetzwerk "Wissen – Können – Handeln" zu den Forschungsergebnissen der Schwerpunktthemen aus der 1. Forschungsphase (2016-2019)). Koblenz: Bundesanstalt für Gewässerkunde. doi: 10.5675/ExpNBS2020.2020.02

Coppola, E., Sobolowski, S., Pichelli, E., Raffaele, F., Ahrens, B., Anders, I., ... others (2020). A first-of-its-kind multi-model convection permitting ensemble for investigating convective phenomena over Europe and the Mediterranean. *Climate Dynamics*, *55*(1), 3–34. doi: https://doi.org/10.1007/s00382-018-4521-8

Crueger, T., Giorgetta, M. A., Brokopf, R., Esch, M., Fiedler, S., Hohenegger, C., ... Stevens, B. (2018). ICON-A, the atmosphere component of the ICON earth system model: II. Model evaluation. *Journal of Advances in Modeling Earth Systems*, *10*(7), 1638-1662. doi: 10.1029/2017MS001233

Davies, H. C. (1976). A lateral boundary formulation for multi-level prediction models. *Quarterly Journal of the Royal Meteorological Society*, *102*(432), 405-418. doi: https://doi.org/10.1002/qj.49710243210

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... others (2011). The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. doi: 10.1002/qj.828

Demory, M.-E., Berthou, S., Fernández, J., Sørland, S. L., Brogli, R., Roberts, M. J., ... Vautard, R. (2020). European daily precipitation according to EURO-CORDEX regional climate models (RCMs) and high-resolution global climate models (GCMs) from the High-Resolution Model Intercomparison Project (HighResMIP). *Geoscientific Model Development*, *13*(11), 5485–5506. doi: 10.5194/gmd-13-5485-2020

Dipankar, A., Stevens, B., Heinze, R., Moseley, C., Zängl, G., Giorgetta, M., & Brdar, S. (2015). Large eddy simulation using the general circulation model ICON. *Journal of Advances in Modeling Earth Systems*, *7*(3), 963-986. doi: https://doi.org/10.1002/2015MS000431

Doms, G., Förstner, J., Heise, E., Herzog, H., Mironov, D., Raschendorfer, M., … Vogel, G. (2018). A description of the nonhydrostatic regional COSMO model. Part II: Physical parameterization. *Deutscher Wetterdienst, Offenbach, Germany*. doi: 10.5676/DWD_pub/nwv/cosmo-doc_5.05_II

Dosio, A., Turner, A. G., Tamoffo, A. T., Sylla, M. B., Lennard, C., Jones, R. G., … Hewitson, B. (2020). A tale of two futures: contrasting scenarios of future precipitation for West Africa from an ensemble of regional climate models. *Environmental Research Letters*, *15*(6), 064007. doi: 10.1088/1748-9326/ab7fde

Ekici, A., Beer, C., Hagemann, S., Boike, J., Langer, M., & Hauck, C. (2014). Simulating high-latitude permafrost regions by the JSBACH terrestrial ecosystem model. *Geoscientific Model Development*, *7*(2), 631–647. doi: 10.5194/gmd-7-631-2014

Gal-Chen, T., & Somerville, R. C. (1975). Numerical solution of the navier-stokes equations with topography. *Journal of Computational Physics*, *17*(3), 276-310. doi: https://doi.org/10.1016/0021-9991(75)90054-6

Gates, W. L., Boyle, J. S., Covey, C., Dease, C. G., Doutriaux, C. M., Drach, R. S., … others (1999). An overview of the results of the Atmospheric Model Intercomparison Project (AMIP I). *Bulletin of the American Meteorological Society*, *80*(1), 29–56.

Giorgetta, M. A., Brokopf, R., Crueger, T., Esch, M., Fiedler, S., Helmert, J., … Stevens, B. (2018). ICON-A, the atmosphere component of the ICON earth system model: I. Model description. *Journal of Advances in Modeling Earth Systems*, *10*(7), 1613-1637. doi: 10.1029/2017MS001242

Giorgi, F., Marinucci, M. R., Bates, G. T., & De Canio, G. (1993). Development of a Second-Generation Regional Climate Model (RegCM2). Part II: Convective Processes and Assimilation of Lateral Boundary Conditions. *Monthly Weather Review*, *121*(10), 2814-2832. doi: 10.1175/1520-0493(1993)121⟨2814:DOASGR⟩2.0.CO;2

Giorgi, F., & Mearns, L. O. (1999). Introduction to special section: Regional Climate Modeling Revisited. *Journal of Geophysical Research: Atmospheres*, *104*(D6), 6335-6352. doi: 10.1029/98JD02072

Grell, G. A., Dudhia, J., & Stauffer, D. R. (1994). *A description of the fifth-generation Penn State/NCAR mesoscale model (MM5)* (No. NCAR/TN-398+STR). Boulder, CO: University Corporation for Atmospheric Research. doi: doi:10.5065/D60Z716B

Gutjahr, O., Putrasahan, D., Lohmann, K., Jungclaus, J. H., von Storch, J.-S., Brüggemann, N., … Stössel, A. (2019). Max Planck Institute Earth System Model (MPI-ESM1.2) for the High-Resolution Model Intercomparison Project (HighResMIP). *Geoscientific Model Development*, *12*(7), 3241–3281. doi: 10.5194/gmd-12-3241-2019

Haarsma, R. J., Roberts, M. J., Vidale, P. L., Senior, C. A., Bellucci, A., Bao, Q., … von Storch, J.-S. (2016). High Resolution Model Intercomparison Project (HighResMIP v1.0) for CMIP6. *Geoscientific Model Development*, *9*(11), 4185–4208. doi: 10.5194/gmd-9-4185-2016

Haylock, M., Hofstra, N., Klein Tank, A., Klok, E., Jones, P., & New, M. (2008). A European daily high-resolution gridded data set of surface temperature and precipitation for 1950–2006. *Journal of Geophysical Research: Atmospheres*, *113*(D20). doi: 10.1029/2008JD10201

Hertwig, E., von Storch, J., Handorf, D., Dethloff, K., Fast, I., & Krismer, T. (2015). Effect of horizontal resolution on ECHAM6-AMIP performance. *Climate Dynamics*, *45*, 185211. doi: 10.1007/s00382-014-2396-x

Hesselberg, A. (1925). Die Gesetze der ausgeglichenen atmosphärischen Bewegungen. *Beiträge zur Physik der Atmosphäre*, *12*, 141–160.

Jones, P., & Harris, I. (2008). *Climatic Research Unit (CRU): Time-series (TS) datasets of variations in climate with variations in other phenomena* *v3. NCAS British Atmospheric Data Centre, May 2021.* Retrieved from http://catalogue.ceda.ac.uk/uuid/3f8944800cc48e1cbc29a5ee12d8542d

Klocke, D., Brueck, M., Hohenegger, C., & Stevens, B. (2017). Rediscovery of the doldrums in storm-resolving simulations over the tropical Atlantic. *Nature Geoscience*, *10*(12), 891–896.

Korn, P. (2017). Formulation of an unstructured grid model for global ocean dynamics. *Journal of Computational Physics*, *339*, 525–552.

Kotlarski, S., Keuler, K., Christensen, O. B., Colette, A., Déqué, M., Gobiet, A., … Wulfmeyer, V. (2014). Regional climate modeling on European scales: a joint standard evaluation of the EURO-CORDEX RCM ensemble. *Geoscientific Model Development*, *7*(4), 1297–1333. doi: 10.5194/gmd-7-1297-2014

Leps, N., Brauch, J., & Ahrens, B. (2019). Sensitivity of limited area atmospheric simulations to lateral boundary conditions in idealized experiments. *Journal of Advances in Modeling Earth Systems*, *11*(8), 2694-2707. doi: 10.1029/2019MS001625

Leuenberger, D., Koller, M., Fuhrer, O., & Schär, C. (2010). A Generalization of the SLEVE Vertical Coordinate. *Monthly Weather Review*, *138*, 3683-3689. doi: 10.1175/2010MWR3307.1

Mauritsen, T., Bader, J., Becker, T., Behrens, J., Bittner, M., Brokopf, R., … Roeckner, E. (2019). Developments in the MPI-M Earth System Model version 1.2 (MPI-ESM1.2) and Its Response to Increasing CO2. *Journal of Advances in Modeling Earth Systems*, *11*(4), 998-1038. doi: 10.1029/2018MS001400

Miguez-Macho, G., Stenchikov, G. L., & Robock, A. (2004). Spectral nudging to eliminate the effects of domain position and geometry in regional climate model simulations. *Journal of Geophysical Research: Atmospheres*, *109*(D13). doi: 10.1029/2003JD004495

Narcowich, F. J., & Ward, J. D. (1994). Generalized Hermite interpolation via matrix-valued conditionally positive definite functions. *Mathematics of Computation*, *63*(208), 661–687. doi: 10.1090/S0025-5718-1994-1254147-6

O'Neill, B. C., Tebaldi, C., van Vuuren, D. P., Eyring, V., Friedlingstein, P., Hurtt, G., … Sanderson, B. M. (2016). The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geoscientific Model Development*, *9*(9), 3461–3482. doi: 10.5194/gmd-9-3461-2016

Pham, T. V., Steger, C., Rockel, B., Keuler, K., Kirchner, I., Mertens, M., … Früh, B. (2021). ICON in Climate Limited-area Mode (ICON release version 2.6.1): a new regional climate model. *Geoscientific Model Development*, *14*(2), 985–1005. doi: 10.5194/gmd-14-985-2021

Prill, F., Reinert, D., Rieger, D., & Zängl, G. (2020). *ICON tutorial: Working with the ICON model.* Deutscher Wetterdienst, Offenbach, www.dwd.de. doi: 10.5676/DWD_pub/nwv/icon_tutorial2020

Rasch, P. J., Xie, S., Ma, P.-L., Lin, W., Wang, H., Tang, Q., … Yang, Y. (2019). An Overview of the Atmospheric Component of the Energy Exascale Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(8), 2377-2411. doi: https://doi.org/10.1029/2019MS001629

Reick, C. H., Gayler, V., Goll, D., Hagemann, S., Heidkamp, M., Nabel, J. E., … Wilkenskjeld, S. (2021). *JSBACH 3 - The land component of the MPI Earth System Model: documentation of version 3.2* (Berichte zur Erdsystemforschung). Hamburg: Max-Planck-Intitut für Meteorologie. doi: 10.17617/2.3279802

Roberts, M. J., Camp, J., Seddon, J., Vidale, P. L., Hodges, K., Vanniere, B., … Ullrich, P. (2020). Impact of model resolution on tropical cyclone simulation using the HighResMIP-PRIMAVERA multimodel ensemble. *Journal of Climate*, *33*(7), 2557 - 2583. doi: 10.1175/JCLI-D-19-0639.1

Rockel, B., Will, A., & Hense, A. (2008). The regional climate model COSMO-CLM (CCLM). *Meteorologische Zeitschrift*, *17*(4), 347–348. doi: 10.1127/0941-2948/

2008/0309

Rummukainen, M. (2010). State-of-the-art with regional climate models. *WIREs Climate Change*, *1*(1), 82-96. doi: 10.1002/wcc.8

Schär, C., Leuenberger, D., Fuhrer, O., Lüthi, D., & Girard, C. (2002). A new terrain-following vertical coordinate formulation for atmospheric prediction models. *Monthly Weather Review*, *130*(10), 2459–2480.

Schulzweida, U. (2020). *CDO User Guide.* doi: 10.5281/zenodo.4246983

Skamarock, W. C., Klemp, J. B., Duda, M. G., Fowler, L. D., Park, S.-H., & Ringler, T. D. (2012). A Multiscale Nonhydrostatic Atmospheric Model Using Centroidal Voronoi Tesselations and C-Grid Staggering. *Monthly Weather Review*, *140*(9), 3090 - 3105. doi: 10.1175/MWR-D-11-00215.1

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Zhiquan, L., Berner, J., ... Huang, X. (2019). *A description of the advanced research WRF model version 4* (No. NCAR/TN-556+STR). Boulder, CO: National Center For Atmospheric Research. doi: 10.5065/1dfh-6p97

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., ... others (2013). Atmospheric component of the MPI-M Earth System Model: ECHAM6. *Journal of Advances in Modeling Earth Systems*, *5*(2), 146–172. doi: 10.1002/jame.20015

Tang, Q., Klein, S. A., Xie, S., Lin, W., Golaz, J.-C., Roesler, E. L., ... Zheng, X. (2019). Regionally refined test bed in E3SM atmosphere model version 1 (EAMv1) and applications for high-resolution modeling. *Geoscientific Model Development*, *12*(7), 2679–2706. doi: 10.5194/gmd-12-2679-2019

Zängl, G., Reinert, D., Rípodas, P., & Baldauf, M. (2015). The ICON (ICOsahedral Non-hydrostatic) modelling framework of DWD and MPI-M: Description of the non-hydrostatic dynamical core. *Quarterly Journal of the Royal Meteorological Society*, *141*(687), 563–579. doi: https://doi.org/10.1002/qj.2378

Zarzycki, C., Jablonowski, C., & Taylor, M. (2014). Using Variable-Resolution Meshes to Model Tropical Cyclones in the Community Atmosphere Model. *Monthly Weather Review*, *142*. doi: 10.1175/MWR-D-13-00179.1

Zhang, D.-L., Chang, H.-R., Seaman, N. L., Warner, T. T., & Fritsch, J. M. (1986). A Two-Way Interactive Nesting Procedure with Variable Terrain Resolution. *Monthly Weather Review*, *114*(7), 1330-1339. doi: 10.1175/1520-0493(1986)114⟨1330:ATWINP⟩2.0.CO;2