Regional Climate Simulations with COSMO-CLM: Ensembles, Very High Resolution and Paleoclimate

G. Schädler, H.-J. Panitz, E. Christner, H. Feldmann, M. Karremann, and N. Laube

Abstract The IMK-TRO (KIT) presents in the HLRS annual report for 2016–2017 projects and their results using the CRAY XC40 "Hazel Hen". The research focuses on the very high resolution regional climate simulations including the modeling of land surface processes and urban climate, the generation of ensemble projections, and regional paleoclimate (PALMOD). The simulations are performed with the regional climate model (RCM) COSMO-CLM (CCLM) and cover spatial resolutions from 50 to 2.8 km. Within the projects, the standard CCLM is enhanced; for the analysis of the impact of different soil-vegetation transfer schemes (SVATs) VEG3D is coupled via OASIS3-MCT to CCLM. For the PALMOD project, a special isotope-enabled version CCLMiso is used. To highlight the added value, the results of the higher resolution climate predictions are compared to those of simulations with coarser resolutions. In addition, the impact of different global driving data sets is investigated. Climate projections are performed for two future time slices, 2021–2050 and 2071–2100. The urban climate and its change are also investigated using very high resolution simulations to enable the energetic optimisation of buildings. The required Wall-Clock-Times (WCT) range from 9 to 2000 node-hours per simulated year.

1 Overview

The working group "Regional Climate and Water Cycle" of the Institute of Meteorology and Climate Research—Tropospheric Research (IMK-TRO) at the Karlsruhe Institute of Technology (KIT) (www.imk-tro.kit.edu) uses the climate version of the COSMO model (COSMO-CLM) on the CRAY XC40 'Hazel Hen' at the HLRS high performance computing facilities to investigate past, present and

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future regional climate with a focus on subregions of Central Europe and Germany. Topics include

- Very high resolution regional climate prognoses and projections
- Urban climate and energetic optimisation of buildings
- Analysis of climate extremes (floods, draughts)
- Assessment of uncertainty via ensemble simulations
- Interaction between land surfaces and the atmosphere
- Simulation of regional paleoclimates

In this report, we describe in some detail three of these topics which are interesting for both their practical relevance and their numerical/computational interest. First, the very high resolution regional climate projections and the simulations concerning urban climate and energetic optimization of buildings; these projects are third-party funded (KLIMOPASS, KLIWA and Baden Württemberg Stiftung). Second, the PALMOD Project, funded by the BMBF, will be presented and the structure of the regional paleo climate simulations illustrated. Third, first results and details to using stable water isotopes to evaluate temperature in paleo simulations are given. Additionally, a description and latest results of the CORDEX project are included.

The text is structured as follows: Sect. 2 describes the model used and Sect. 3 contains the CORDEX (Sect. 3.1) and the PALMOD project (Sect. 3.2), and also the very high resolution simulations (Sect. 3.3).

2 The CCLM Model

The regional climate model (RCM) COSMO-CLM (CCLM) is the climate version of the operational weather forecast model COSMO (Consortium for Small-scale Modeling) of DWD. It is a three-dimensional, non-hydrostatic, fully compressible numerical model for the atmosphere. The model solves prognostic equations for wind, pressure, air temperature, different phases of atmospheric water, soil temperature, and soil water content.

Further details on COSMO and its application as a RCM can be found in [1, 2] and on the web-page of the COSMO consortium (www.cosmo-model.org).

3 Regional Climate Simulations Using the HLRS Facilities

3.1 CORDEX (Coordinated Regional Downscaling Experiment) Project

Since the United Nations climate change conference in Paris in December 2015 (COP21) the optimistic Representative Concentration Pathway 2.6 (RCP2.6, [3])

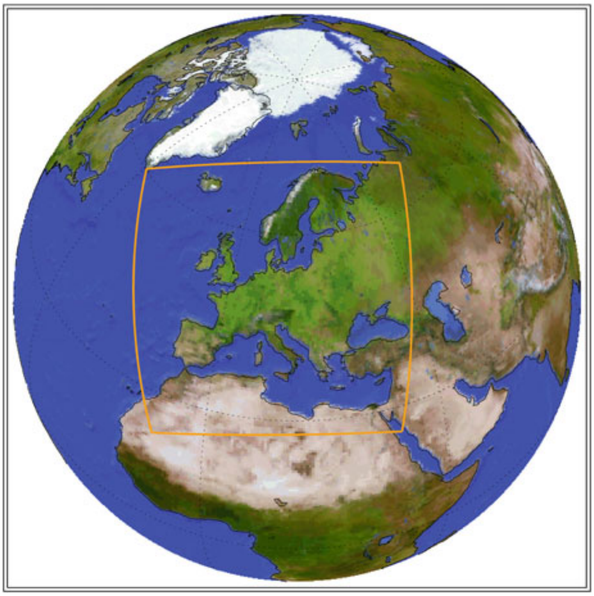


Fig. 1 The EURO-CORDEX domain; see also www.cordex.org

came into the focus as the future scenario for which the global mean temperature increase can be kept below +2 °C [4]. RCP2.6 assumes that global annual Green-House-Gas GHG emissions (measured in CO2-equivalents) peak between 2010–2020, with emissions declining substantially thereafter. In order not only to consider the global aspect, there is also an increasing demand to study the response of regional climate to RCP2.6. Up to now, the matrix of regional climate simulation under RCP2.6 is rather sparse, however. Therefore, we regionalized results of the global model EC-EARTH, realization 12, with RCP2.6 for the EURO-CORDEX region (Fig. 1). The spatial resolution of these CCLM simulations is 0.11° (about 12 km) and spans the period from 2006 until 2100. The GCM EC-EARTH and its realization 12 have been used because the same global model in its realization 12 has already been downscaled with CCLM on the same 0.11° domain, but assuming the future scenarios RCP4.5 and RCP8.5 [5].

The impact of the different emission scenarios is most pronounced in the future trends of the near-surface temperature in 2 m height (Fig. 2). For the future scenario RCP 8.5 and averaged over the whole EURO-CORDEX domain (Fig. 2, red curve), the mean yearly temperature in 2 m height increases up to about 4.5 °C at the end of the twenty-first century, relative to a 30 years reference period from 1971 until 2000. For RCP4.5, the temperature is also rising, but seems to stabilize at the end of the current century. However, applying RCP2.6, the temperature increases slightly until around 2060, and then seems to decrease again.

Note that the example shown in Fig. 2 represents temporal and spatial averages, temporal averages over each year, and spatial ones over the whole model domain. Considering different seasons and different regions in Europe, the results will be

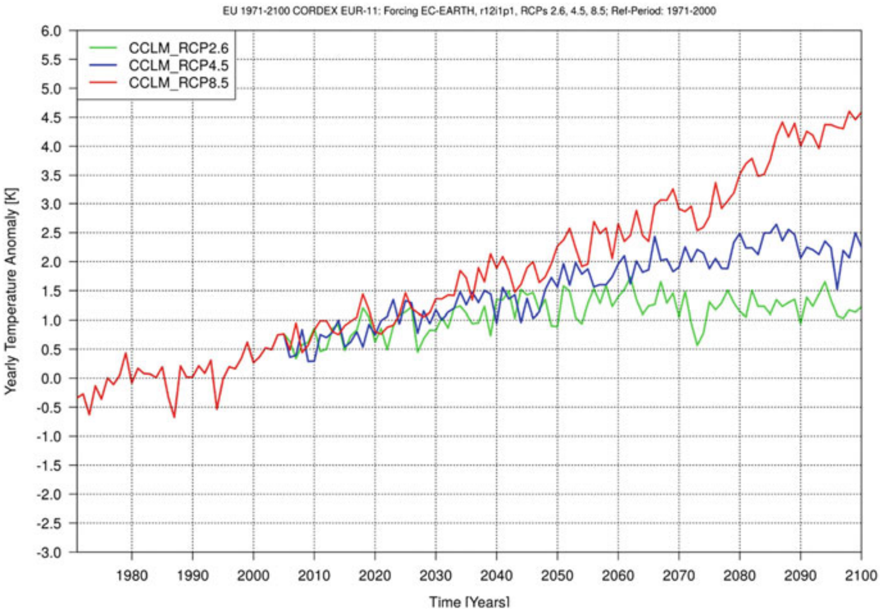


Fig. 2 Yearly 2 m temperature anomaly under different future emission scenarios. Reference period: 1971–2000, regional climate model: CCLM, Version 4-8-17; driving GCM: EC-EARTH, realization 12. Green line: result assuming RCP2.6, Blue line: result assuming RCP4.5, red line: result assuming RCP8.5

qualitatively similar to those shown in Fig. 2, but quantitatively they might differ considerably from season to season and from region to region. A more detailed analysis of the results is still ongoing. Note too, that the basis of the results discussed so far is the regionalization of a single GCM by only one RCM. To investigate the robustness of the results it is necessary to consider a multi member ensemble consisting of several GCMs that have been downscaled by several RCMs. The climate simulations described here will be part of such a multi member ensemble. A final analysis of this ensemble is pending. The HPC resources needed for the CORDEX simulations were in the order of 32,000 node-hours for the computations, and 90 TB for the total data storage. It should also be mentioned that these simulations had been used by members of the CRAY staff at HLRS to analyse the variations of wall-clock-time (WCT) we reported in our HLRS report 2015 [6]. In order to carry out the analysis it was necessary to implement in the code special routines for time-measurements, which sent real-time information to the CRAY staff. We do not know whether any causes for the WCT variations could be detected. However, WCT variations up to 20% and more still exist.

3.2 Regional Paleoclimate Simulations

The Paleo Modeling project PALMOD (www.palmod.de) aims to improve the understanding and modeling of paleoclimate system dynamics and variability. Therefore, fundamental processes determining the Earth's climate trajectory and variability during the last glacial cycle need to be identified and quantified. Our working group contributes to two work packages within the project: "Physical System: Scale Interactions" and "Proxy Data Synthesis/Data-Model Interface". The aim of the first work package is to identify and understand relevant subgrid scale processes, which significantly contribute to the Greenland ice sheet surface mass balance. Such processes can not be resolved with coarse resolution GCMs and, therefore, need to be parameterized. In the second work package, we apply CCLM to validate regional simulations of paleoclimates against water isotope records and provide a combined model-data framework for the interpretation of proxy data.

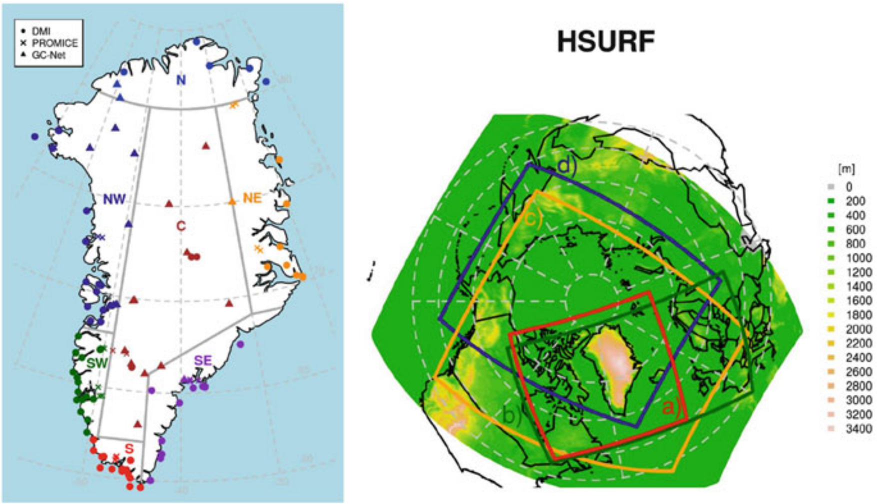
3.2.1 Modeling of the Greenland Surface Mass Balance

For the identification of subgrid scale key processes, we adapted and set up the regional climate model CCLM for the Greenland region. The model was driven with ERA-Interim reanalysis data for the period of 1992–2015 using the SVAT TERRA-ML. Sensitivity tests concerning e.g. the modeling domain, the time step, the horizontal resolution or the inclusion of sea ice were performed.

Comparisons between simulations performed with CCLM and observation data show a generally good agreement throughout Greenland. However, the quality of simulations depends on the analysed region (Fig. 3a), the season and the variable (precipitation or temperature). Simulations are also sensitive to the modeling domain, the resolution and the impact of sea ice. Best agreement of simulations and observation data (Fig. 3a) is found for the CORDEX-Arctic region (Fig. 3b) as modeling domain on a resolution of 25 km and a time step of 150 s. Moreover an increase of the value of the maximum albedo as well as the implementation of sea ice lead to better agreement with observation data. Fig. 4a, b show a comparison of the CCLM results with three different observational data sets for the southwestern region in February (Fig. 4a) and the northern region in June (Fig. 4b). There is a good agreement in the medians in both cases, but a larger data spread within and between the different data sets.

3.2.2 Modeling of Stable Water Isotopes in the Arctic Region

Stable isotopes of atmospheric water such as $H_2^{16}O$ and $H_2^{18}O$ are fractionated during phase changes. This is measured as $\delta^{18}O = R_{^{18}O}/R_{^{18}O,VSMOW} - 1$ with the isotope ratio $R_{^{18}O} = [H_2^{18}O]/[H_2^{16}O]$ and the ocean water ratio $R_{^{18}O,VSMOW} = 0.002005$.



(a) (b)

Fig. 3 (**a**) Location of measuring stations used for validation of the model: Danish meteorological Institute (DMI; dots), Programme for Monitoring of the Greenland Ice Sheet (PROMICE; x), and of the Greenland Climate network (GC-Net; triangles). Colours show seven analyzed regions of Greenland: north (N; blue), northwest (NW; dark blue), central (C; brown), northeast (NE; orange), southwest (SW, green), south (S; red), and southeast (SE, purple). (**b**) Orography [m] and modeling domains: a) region around Greenland. b) Region covering almost region a) but extended towards Europe. c) Modeling area covering parts of Europe and crossing the north pole. d) CORDEX-Arctic region

In this context, an effect of particular importance is the gradual decrease of δ^{18}O in cooling and raining air masses, which are depleted in $H_2^{18}O$ because of a preferential fractionation of the heavier $H_2^{18}O$ into the condensate. The resulting general relation between air temperature and the δ^{18}O of water vapor or precipitation (e.g.[7, 8]), in turn, allows reconstructing variations of air temperature in the past from Arctic ice sheets, which record the δ^{18}O of precipitation from thousands of centuries [9].

Within the PALMOD project, the relation between δ^{18}O and temperature is used for validating paleo simulations with general circulation models (GCMs) against the δ^{18}O in ice core samples from Greenland. To allow a direct comparison between the model and the δ^{18}O in ice cores, isotope physics was implemented into the employed GCMs. To account for the relatively low horizontal resolution of the GCMs, KIT uses an isotope-enabled version [10] of the regional CCLM model (CCLMiso) for a dynamical downscaling of the global paleo simulations.

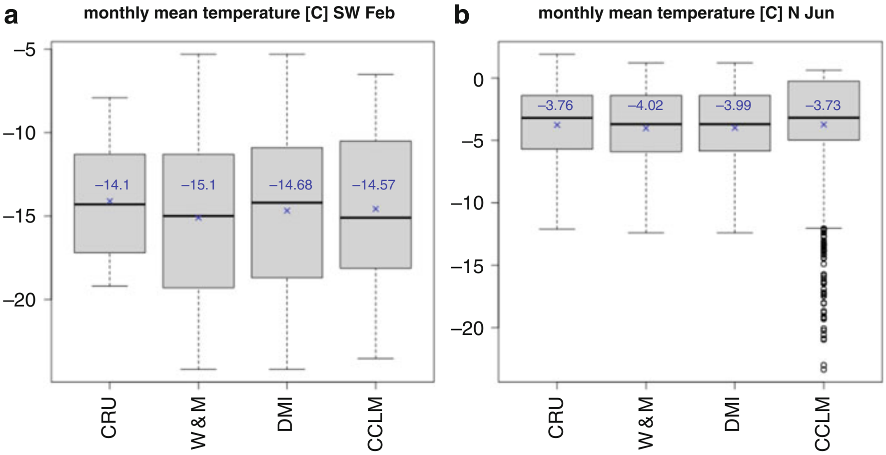


Fig. 4 Box-Whisker-plots for monthly mean temperature in 2 m for "Climate Research Unit" (CRU), "Willmott and Matsuura" (W & M), "Danish meteorological Institute" (DMI) and CCLM simulations on 25 km resolution using the CORDEX-Arctic region as modeling area. Blue: monthly mean of all grid points (**a**) south west Greenland in February 2001. (**b**) North in June 2001

In a first step, we validated present-day CCLMiso simulations for the Arctic region against the δ^{18}O of top core samples from ice cores and snow pits (Fig. 5). CCLMiso is capable of capturing the observed spatial distribution of δ^{18}O. The RMSE between the modeled and the observed δ^{18}O is only 1.6‰. For the arctic region, both findings confirm that the most important isotpe physics is reliably implemented. In a next step, the validated CCLMiso may therefore be used for paleo simulations of the Arctic region and a comprehensive translation of the $\delta^{1}8$O in Greenland ice cores into paleo temperatures.

Table 1 summarizes the computing demands on CRAY XC40 "Hazel Hen" at HLRS for the simulations. Due to the increase of prognostic equations, the computational costs of isotope modeling are considerably higher than comparable simulations that do not consider isotopes.

3.3 Very High Resolution Simulations

3.3.1 Added Value of Very High Resolution Simulations

As already done operationally for weather forecasts, climate simulations at very high spatial horizontal resolution in the order of 1–3 km are becoming now feasible. Apart from the increasing demand for such simulations—they reduce the scale gap between climate models and impact models (urban climate, hydrological and agricultural models often run at resolutions of a few hundred meters)—there

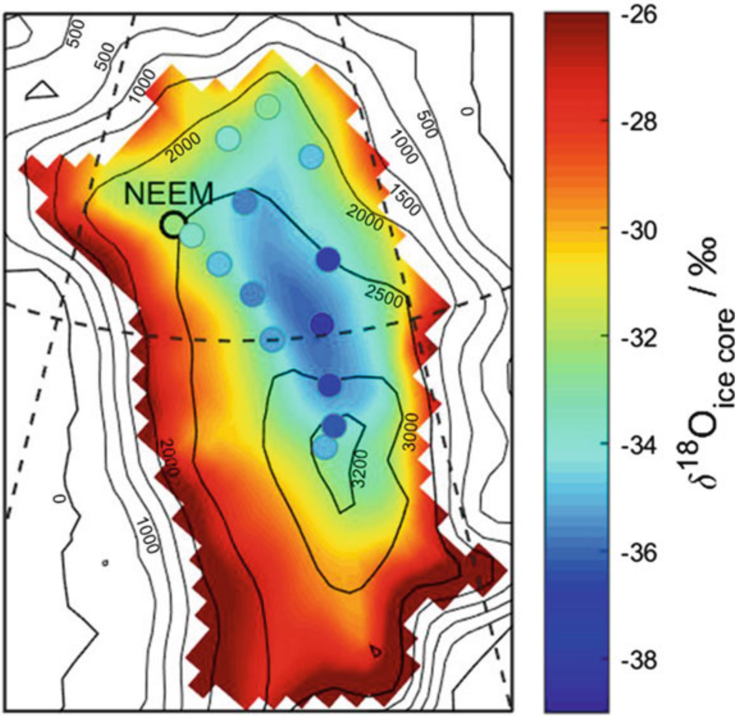


Fig. 5 Regional present-day (2000–2014) simulation with CCLMiso for Greenland. Colored area: accumulation-weighted annual model values of δ^{18}O; colored dots: respective annual δ^{18}O in top core samples from ice cores and snow pits of [11]

Table 1 Project PALMOD: Summary of computing demands on CRAY XC40 "Hazel Hen" at HLRS

Project	Domain size	Grid resolution (km)	Time-step (s)	Computing time (node-h/year)	No. of sim. years	Storage needs (Gbyte/year)	Total computing time (node-h)	Total storage needs (Tbyte)
PALMOD	246 ∗ 120 ∗ 50	50	120	190	350	300	66,500	11

are also physical and numerical pros for very high resolution: a considerable reduction, if not an elimination of the model bias, i.e. the systematic difference between model results and observations, can be obtained. This is due to a better representation of orography and land cover as well as an explicit calculation of deep convective precipitation instead of a parameterisation. Moreover, a high spatial resolution induces a more realistic small scale temporal and spatial variability of meteorological variables due to a better representation of the orography and land use patterns, which is especially true in complex terrain. This small scale variability is also important to capture weather extremes more realistically and to better represent persistent and therefore climatically relevant small scale features like local/regional wind, precipitation systems, and temperature regimes.

In [12], it had already been demonstrated that the quality of the model results could be improved due to a refinement of the resolution of the climate model. Altogether, model simulations at 2.8 km horizontal resolution provide an added value compared to coarser resolutions (for example, 7 km) for temperature, precipitation, relative humidity, global radiation, and regional wind systems, even though the magnitude of the added value varies with variable, season, region, altitude and statistics [12]. This makes the high resolution data more suitable for applications and impact studies on regional or local scales where high resolution is required, e.g. in cities or small river catchments. It can also be expected that higher variability improves the tails of probability distributions, i.e. the representation of extremes.

After having shown that there is an added value of very high resolutions, we started to work on two projects involving very high resolution simulations.

3.3.2 Simulations of Present and Future Climate

In the frame of the project KLIWA (Klimaveränderung und Konsequenzen für die Wasserwirtschaft) we started to generate very high resolution (about 2.8 km) regional climate projection ensembles focusing on an area that comprises the basins of major rivers of the southern part of Germany (e.g. Rhine, Moselle, Danube, Inn). The first GCM that we downscaled in a three-stage nesting approach was ECHAM6, realisation 1. The three-nest approach regionalized the GCM data down to a resolution of 50 km in the first step. The second step uses the RCM result of the first step and performs the downscaling to 7 km, and in the third step the final resolution of 2.8 km is reached. The historical control period ranges from 1968 to 2005, for the future we consider the periods 2018 until 2050 and 2068 until 2100 using emission scenario RCP8.5 [3]. For all three periods, the first 3 years are considered as spin-up time, and they are not used in the analyses of the results. In order to establish a small ensemble, two other GCMs, namely HadGEM2-ES, realization 1, and EC-EARTH, realization 12, have been downscaled, again applying the three-nest approach. In its finest resolution of 2.8 km the downscaling of HadGEM2-ES is already finished for the historical control period. The EC-EARTH driven simulation for the historical period is close to its end.

Table 2 summarizes the computing demands on CRAY XC40 "Hazel Hen" at HLRS for the three-nest downscaling of one GCM, taking into account the number of simulation years of all three periods considered.

The model domain for the very high resolution (2.8 km) simulations covers large parts of Germany and neighboring regions, having a size of $322 * 328$ horizontal grid-points. The analyses of results are performed in the region marked by the red box in Fig. 6.

Table 2 Project KLIWA2.8: Summary of computing demands on CRAY XC40 "Hazel Hen" at HLRS for the three-nest downscaling of one GCM

Project	Domain size	Grid resolution (km)	Time-step (s)	Computing time (node-h/year)	No. of sim. years	Storage needs (Gbyte/year)	Total computing time (node-h)	Total storage needs (Tbyte)
Very high resolution	$118 * 110 * 40$	50	360	9	203	115	1827	24
KLIWA 2.8 km Ensemble	$165 * 200 * 40$	7	60	33	203	300	6699	61
in three nest approach	$322 * 328 * 49$	2.8	25	2000	104	500	208,000	52
Total amount				2042	510	915	216,526	137

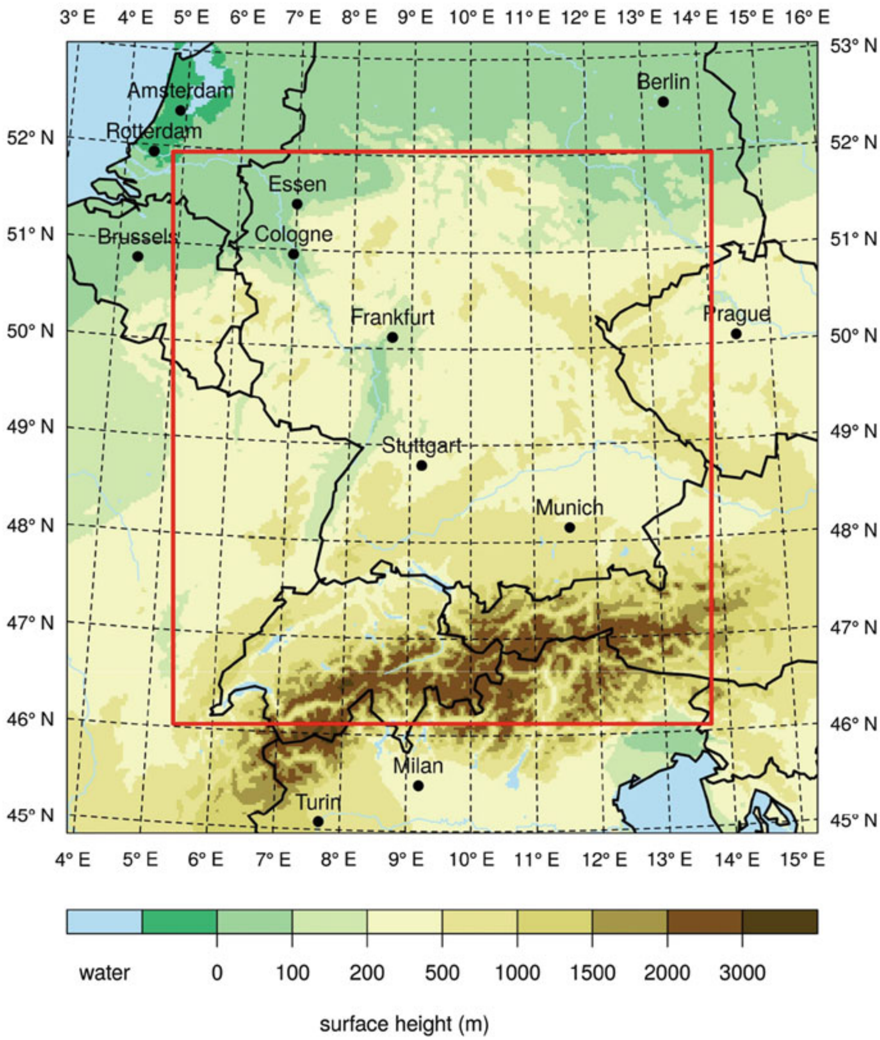


Fig. 6 KLIWA project. Actual model domain for very high resolution simulations and its orography. The red box encloses the region where results are analysed

Figure 7 displays the annual mean daily precipitation sums for 1971–2005, resulting from CCLM simulations with MPI-ESM-LR, EC-EARTH and HadGEM2-ES forcings, and compares them with the gridded EOBS V.11 observations [13]. This comparison reveals a general wet bias of the model results, whose amount strongly depends on the driving GCM.

In Fig. 8, a comparison between the CCLM_MPI-ESM-LR third nest (2.8 km) and the CCLM_MPI-ESM-LR second nest (7 km) to HYRAS observations [14] is displayed in terms of whisker box plots indicating the 25, 50 and 75 percentiles.

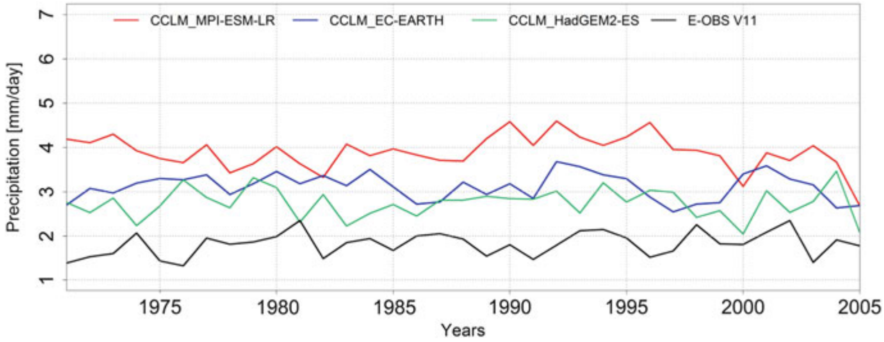


Fig. 7 1971–2005 Annual mean daily precipitation sums for three CCLM simulations using the MPI-ESM-LR (red), EC-EARTH (blue) and HadGEM2-ES (green) forcing for the KLIWA evaluation area

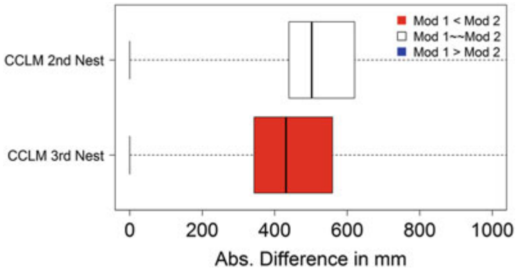


Fig. 8 1971–2000 Boxplot comparing the difference of the annual precipitation sums of CCLM_MPI-ESM-LR third nest (2.8 km) to HYRAS to the difference CCLM_MPI-ESM-LR second nest (7 km) to HYRAS. The coloring of the box displays the 95 percentile significance level (Wilcoxon test). Red indicates the significantly lower differences to HYRAS of the CCLM_MPI-ESM-LR third nest than the CCLM_MPI-ESM-LR second nest

A Wilcoxon test with a significance level of 95% was performed. In Fig. 8 the red box indicates a significantly better agreement of the higher resolved third nest to HYRAS observations.

3.3.3 Urban Climate: Performance Criteria for Indoor Comfort Wall-Building Materials Under the Influence of the Climate Change in Baden-Württemberg ("Room/Climate/Plaster")

Under changing environmental conditions—which are a consequence of global climate change—living comfort should be maintained. Expected changes of temperature and humidity, which affect the living comfort of people, are analyzed in the project. The study is performed in the framework of a project, funded by the Baden-Württemberg Stiftung, that couples the outdoor and the indoor climate as well as the thermal-hygric behavior of walls by thermal-energetic building simulations driven with regional climate model data. The intention is to avoid too wet and sultry indoor climate by passive plaster systems.

The project is divided in three parts, which correspond essentially to the spatial scales weather and climate ("climate"), room climate and user behavior ("room") as well as building envelope and material behavior ("plaster"). The part "climate" is processed by IMK-TRO and serves as basis for the other two parts, as the resulting climate data output are the boundary data for the impact simulations (thermal-energetic building simulations and moisture transport simulations in walls and multi-layer building components). For these simulations hourly weather data (temperature, humidity, pressure, radiation, precipitation and wind) in the epw (EnergyPlus Weather Data)-format was built and provided by IMK-TRO.

The high resolution regional climate simulations were performed with CCLM, which was driven by data from the GCM ECHAM6 for projection, and ERA Interim reanalysis for validation. The global data are dynamically downscaled with CCLM up to a convection permitting mesh size of 2.8 km. The dynamical downscaling of ECHAM6 data, which have a resolution of about 180 km, is done via two nests (55 and 11 km) to the target resolution of convection permitting 2.8 km. ERA-Interim data, having already a grid-spacing of about 75 km, are scaled down via an 11 km nest to 2.8 km mesh size. The 11 km runs cover the whole of Europe, the 2.8 km runs cover Baden-Württemberg and surrounding areas; past (1981–2010) and future (2021–2050) periods are considered. To estimate the range of possible future developments, an ensemble is created by:

- the use of two emission scenarios, RCP4.5 and RCP8.5,
- coupling COSMO-CLM with the SVAT VEG3D as a more complex alternative scheme to the reference SVAT TERRA-ML,
- and climate simulations with different GCMs as forcing models, which were already available at IMK-TRO.

Table 3 summarizes the computing demands on CRAY XC40 "Hazel Hen" at HLRS for these simulations for a single driving GCM.

The focus of the evaluation of the data lies on sultry conditions in summer in Baden-Württemberg. To identify for the large-scale atmospheric conditions of sultry weather in Baden-Württemberg, the objective weather type classification of the DWD [15] was used. By viewing the results of the validation run, warm and humid conditions in Baden–Württemberg show a strong dependency on the large scale flow conditions. Using the dew point temperature as an indicator for warm and humid conditions, most of these conditions result from the southwesterly weather type SW, followed by undefined directions XX (see Fig. 9). Relative to the total occurrence of weather types of one direction (sector), in summer even 2/3 of the southeasterly SE and also 1/4 of the southwesterly SW weather patterns produce sultry conditions.

Table 3 Summary of computing demands on CRAY XC40 "Hazel Hen" at HLRS for the project room/climate/plaster of one GCM

Project	Domain size	Grid resolution (km)	Time-step (s)	Computing time (node-h/year)	No. of sim. years	Storage needs (Gbyte/year)	Total computing time (node-h)	Total storage needs (Tbyte)
Room/climate/plaster	$160 \times 120 * 40$	55	400	12	170	75	2040	13
Ensemble three nest approach	$320 \times 360 * 40$	11	80	260	175	2500	66,300	437
	$140 \times 150 * 50$	2.8	25	300	265	800	93,000	212
Total amount				572	735	3375	161,340	662

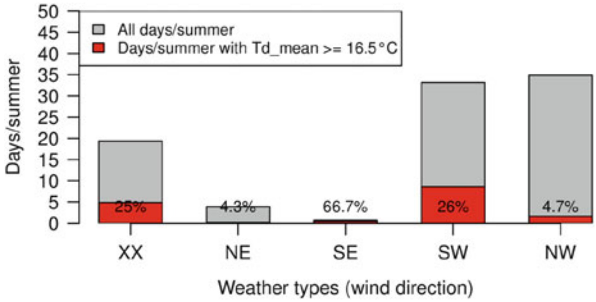


Fig. 9 Weather types in summer (mean of 1981–2010) sorted with respect to wind directions. XX is undefined direction (<2/3 of all viewed grid points not in one wind direction sector); NE = North East, SE = South East, SW = South West, NW = North. The grey bars represent the total number of directions, the red bars the total number of directions, which cause a daily mean of the dew point temperature $\geq 16.5\,°C$ at a grid point near Karlsruhe. The numbers show the height of the red bars relative to the grey bars

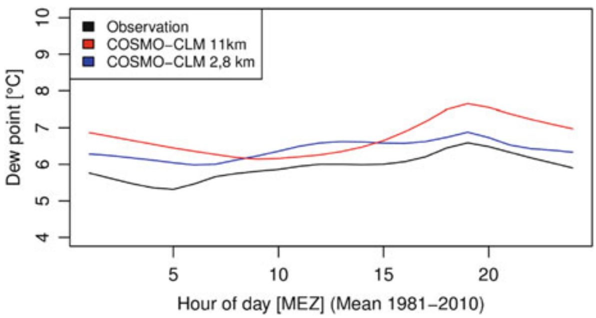


Fig. 10 Comparison between observation data (black line; meteorological tower at KIT near Karlsruhe) and model data with horizontal resolutions of 11 km (red line) and 2.8 km (blue line). The daily cycles of the dew point temperature averaged from 1981 to 2010 are shown

The evaluation of the finer grid runs is currently in progress. An example for a benefit of a combined humidity and temperature measure is shown in Fig. 10. It shows the daily cycle of the dew point temperature averaged from 1981–2010. The observation data are from the 200 m meteorological tower at KIT (near Karlsruhe). From the models (forcing data: ERA-interim, first nest 11 km, second nest 2.8 km) the nearest grid point to the tower location was chosen. The 2.8 km run (blue line) shows better agreement with the observations (black line) in the statistics and in the shape of the curve than the 11 km run (red color). Further evaluations related to sultry conditions like the influence of urban surfaces or local wind systems are in progress.

4 Remarks on the Nesting Strategy and Its Computational Aspects

Dynamical downscaling is used in regional climate modelling to transfer large scale information to the regional scale. Basically, this method is a nesting of the regional climate model (RCM) into large-scale global climate model (GCM) projections or reanalyses. This means that the model is initialized once with a state derived from the large scale information and that this information is updated at the lateral boundaries of the regional model domain at regular time intervals.

The horizontal grid sizes of the global data sets are generally considerably larger than 100 km. To avoid too large jumps in the grid sizes, especially if the ultimate goal are regional climate simulations at very high spatial horizontal resolution in the order of 1–3 km, a multiple nesting technique is used for the dynamical downscaling. The advantages of multiple nests and of regional simulations at very high spatial horizontal resolutions are discussed in [12], for example. The technique of multiple nesting is illustrated in Fig. 11. It has to be pointed out that, with respect to the application of CCLM, the multiple nesting requires consecutive simulations, one for each nest. Local grid refinement is not possible in CCLM.

Fig. 11 From global resolution to very high regional resolution: illustration of the multiple nesting strategy (here two nests) used in CCLM applications (courtesy of Süddeutsches Klimabüro: http://www.sueddeutsches-klimabuero.de/)

In a first nesting step the global scale data are used to drive a CCLM simulation with the coarsest horizontal grid size, here 0.44° (about 50 km in mid-latitudes, the "European" scale in Fig. 11). In the second step the results of this regional coarse grid simulation are used to drive CCLM simulations with finer grid spacing (here 0.0625°), in general with more specific regional or even local focus (for example, the "German" scale in Fig. 11). This procedure is continued down the final very high resolution scale (here 0.025°).

Of course, going from coarser grid to finer ones does not necessarily imply a reduction of the geographical size of the model domain. However, one has to keep in mind that a refinement of the horizontal grid spacing by a factor of two and keeping the domain of the coarse grid would increase the computational needs considerably. The required storage capacity would increase by a factor of four. Roughly, the computing time would increase by a factor of eight, because not only the total number of horizontal grid points would increase by a factor of four, but also the numerical time step has to be reduced by factor of two at least. Of course, the real increase of computing time would be less than the "linear" estimate because more horizontal grid points would allow the usage of more computational nodes. However, the number of cores and thus the number of nodes that sensibly can be used is limited by the number of grid-points in each horizontal coordinate direction and by the numerical advection scheme used. Experience with the CCLM model shows that the ratio between the number of grid points and the number of computational cores in each horizontal direction should be in the order of ten in order to achieve a good balance between the times needed for the pure computations and the communication between parallel cores.

As already said, a nest with refined grid spacing often focuses on regions that have a smaller geographical size than the region represented in the nest with coarser resolution. However, this does not necessarily imply that the number of grid points considered also becomes smaller. On the contrary, this number might even increase, as demonstrated, for example, in Tables 2 and 3. Together with the smaller numerical time steps, the computational needs for the simulations in the nests with higher resolution are considerably larger than for the first nest with 50 km resolution.

Thus, the consideration of multiple nests with consecutive refinements of the horizontal grid spacing has not necessarily a computational benefit. But, and more important from the viewpoint of a climate researcher, there is certainly a scientific benefit as demonstrated by Hackenbruch et al. [12].

The benefit (the speedup) of using the nesting compared with running a whole domain in finer resolution can also roughly be deduced from the first lines in Table 2 (and Table 3), since both simulations presented there only differ in the spatial resolution, the number of horizontal grid points, and the numerical time step. Performing the simulation of the first nest with a resolution of 7 km instead of 50 km would increase the number of horizontal grid points by about a factor of 49, and the time-step would have to be reduced by factor of six. Assuming that the number of cores used does not change, the computational need would roughly increase by a factor of 294, leading to a computational time of 2646 node-hours per simulation year. Theoretically, due to the larger number of grid-points, about 266 nodes could be used for the higher resolution case (7 km) compared to six for the 50 km case. Thus, the computational time would be in the order of 60 (= 2646/44) node-hours per simulation year. However, this is still larger than the sum of the computing times, which is 41 node-hours per simulation year, for the two consecutive nesting steps.

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