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Project Title: NUKLEUS – Actionable local climate information for Germany
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Project overview

This is the initial DKRZ computing time proposal for the projects NUKLEUS and ISAP, which are contributions to the BMBF funded research program RegIKlim.

What will climate change look like in your region? Which adaptation measures are necessary and useful? The new BMBF funded research program RegIKlim (Regional information for action on climate change; German: Regionale Informationen zum Klimahandeln) aims to provide answers to these questions.

The effects of climate change vary widely from region to region. However, reliable information for regions and cities is still missing. The aim of the research program is therefore to develop decision-relevant knowledge on climate change in municipalities and regions and to create a sound basis for regionally specific information and evaluation services. In the first phase of RegIKlim 6 so called “model regions” have been selected, which cover a wide range of geographical and social-economic conditions. The regions include Northern German coastal regions, Eastern German agricultural and forested areas as well as lower mountain ranges, a pre-Alpine region, the city of Stuttgart and its surrounding municipalities and the port of Duisburg including the Rhine. Based on climate change signals and spatial and landscape conditions, information tools for decision support for regional adaptation to climate change will be developed. In addition, basic aspects of adaptation are investigated for the regions. The focus should be on adaptation capacity and the integrated assessment of climate risks and options for action.

An important basis for action recommendations for adaptation measures are projections of the climatic changes that are created with regional climate models. This task is addressed by the RegIKlim cross-cutting activity NUKLEUS (Actionable local climate information for Germany; German: Nutzbare lokale Klimainformationen für Deutschland). Therefore, NUKLEUS develops and implements a strategy to deliver an unprecedented ensemble of very high-resolution climate change simulations on a kilometre-scale for Germany.

The NUKLEUS consortium consists of partners from the Helmholtz-Centre HEREON (HZH), the Karlsruhe Institute of Technology (KIT), the Brandenburg University of Technology Cottbus-Senftenberg (BTU), the University Würzburg (UW), the Justus-Liebig University Gießen (JLU), the Technical University Dresden (TUD) and the German Climate Computing Center (DKRZ). The project is structured into three work packages:

- AP1 regional Climate Modelling
- AP2 Evaluation and Assessment
- AP3 Interfaces to impact models and stakeholders

Planned work, performed simulations, summary of (preliminary) results

The RegIKlim model regions, which address different regions all over Germany, require very high-resolution (spatial as well as temporal) climate information for local scale impact modelling decision support systems. To cover the project needs, a dedicated downscaling strategy is applied within NUKLEUS:

Three dynamical regional climate models (RCM) will be applied within the project to cover the uncertainty range of the representation of regional scale processes – namely REMO, COSMO-CLM and ICON-CLM. Whereas REMO (Jacob, 2001) and COSMO-CLM (CCLM; Rockel et al., 2008) are well established RCMs, which have been used in many previous studies, ICON-CLM (Van Pham et al., 2021) is a newly developed regional climate model, derived from the ICON icosahedral nonhydrostatic model (Zängl et al., 2009) and has to be optimized for the requirements of the project.

In a first step a dynamical downscaling of the global climate simulation to the EURO CORDEX EUR-11 grid (~12 km) is performed, followed by a second step to convection permitting scales of 3 km resolution (CEU-03 domain). For ICON with its icosahedral grid, comparable model domains have been chosen.

In addition, statistical-dynamical and statistical downscaling will be applied as well, especially for the highest resolution.

A further pre-condition is up-to-date forcing data, which means using boundary conditions to the newly available CMIP6 global climate projections. Several CMIP6 simulations will be downscaled to cover the uncertainty range of these climate projections.

A post-processing including data standardisation (cf. Data Management) and bias adjustment will be performed.

The NUKLEUS simulations should be part of the next generation (EURO-)CORDEX regional ensemble based on CMIP6 however, the community did not finalize a simulation protocol until July 2021. Several members of NUKLEUS participate actively in these activities.

To not further waste computing time the members of the NUKLEUS project decided to move forward with the planned simulations based on the most recent draft simulation protocol of EURO-CORDEX. If needed, NUKLEUS will include adjustments coming from the final EURO-CORDEX protocol in the NUKLEUS climate change simulations planned for the upcoming computing time application period.

Therefore, during the first 6 month of the project we were only able to perform test simulations for model tuning and domain configurations.

For 2021 ERA5 driven evaluation simulations were planned in both resolutions. In the first month of this year, the models have been tested and optimized. Soon, the production will start.

Optimization and testing

<u>REMO</u>

With REMO mainly tuning exercises have been performed during the last 6 months. The main focus was on optimizing the new model version (most likely called REMO2021) compared to the last release (REMO2015). The new model version includes several bug fixes and new/changed parametrization schemes. A publication on details of the changes and an overall performance analysis is in preparation. Figure 1 shows the differences in seasonal precipitation compared to E-OBS v21.0 for a ten-year period (2001-2010) over Germany (simulations were run on the entire EURO-CORDEX domain). For both model versions ERA-Interim data were used as boundary conditions. The new REMO version shows a clear reduction in spatial differences that are mainly related to orographically forced precipitation. Long standing issues like “grid-box” storms leading to strong checker-board-like patterns in the differences could be eliminated. Figure 2 shows the same as Figure 1 but for near-surface temperature. For Germany, not a lot of changes can be seen, but here REMO2015 was already performing quite well. In general, further analyses (not shown) confirm that the new REMO version outperforms REMO2015 in the entire EURO-CORDEX domain.

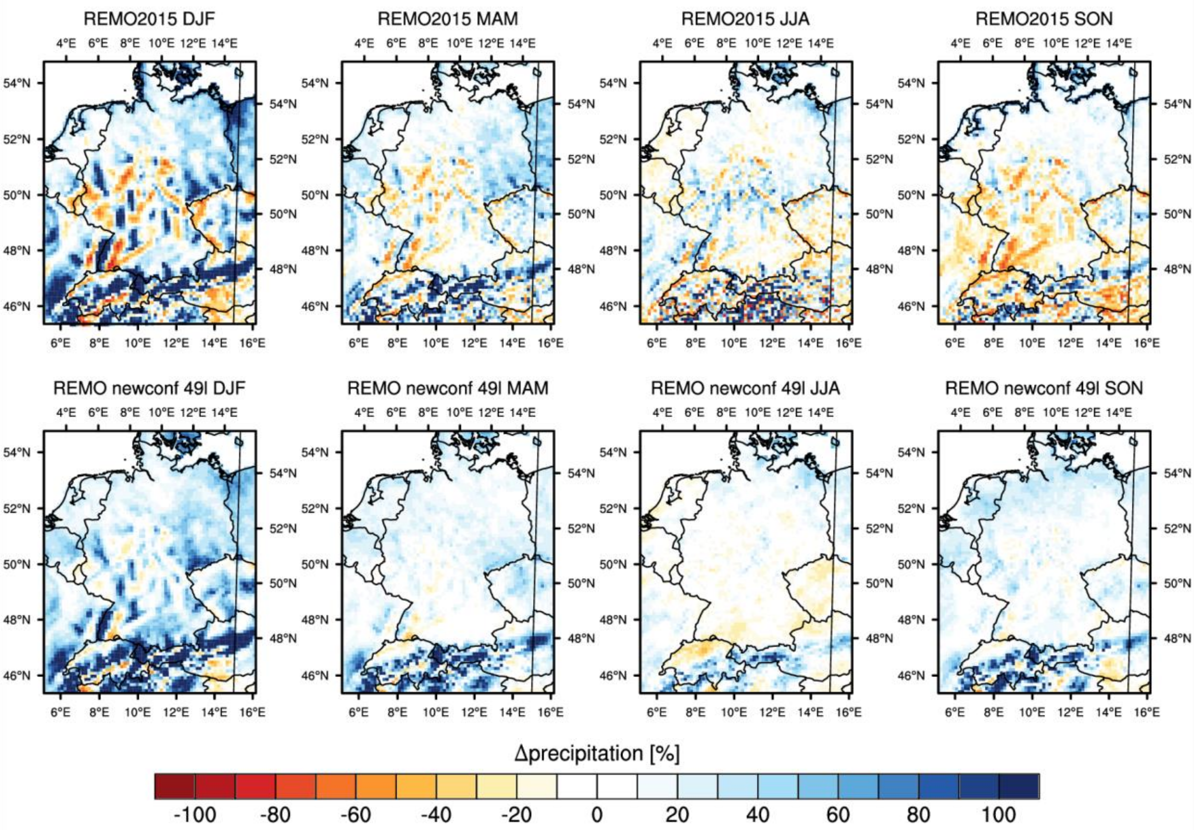

Fig. 1: Differences [%] of seasonal mean precipitation compared to E-OBS v21.0 for a ten year period (2001-2010). The top row shows REMO2015 and the lower one the new realease candidate.

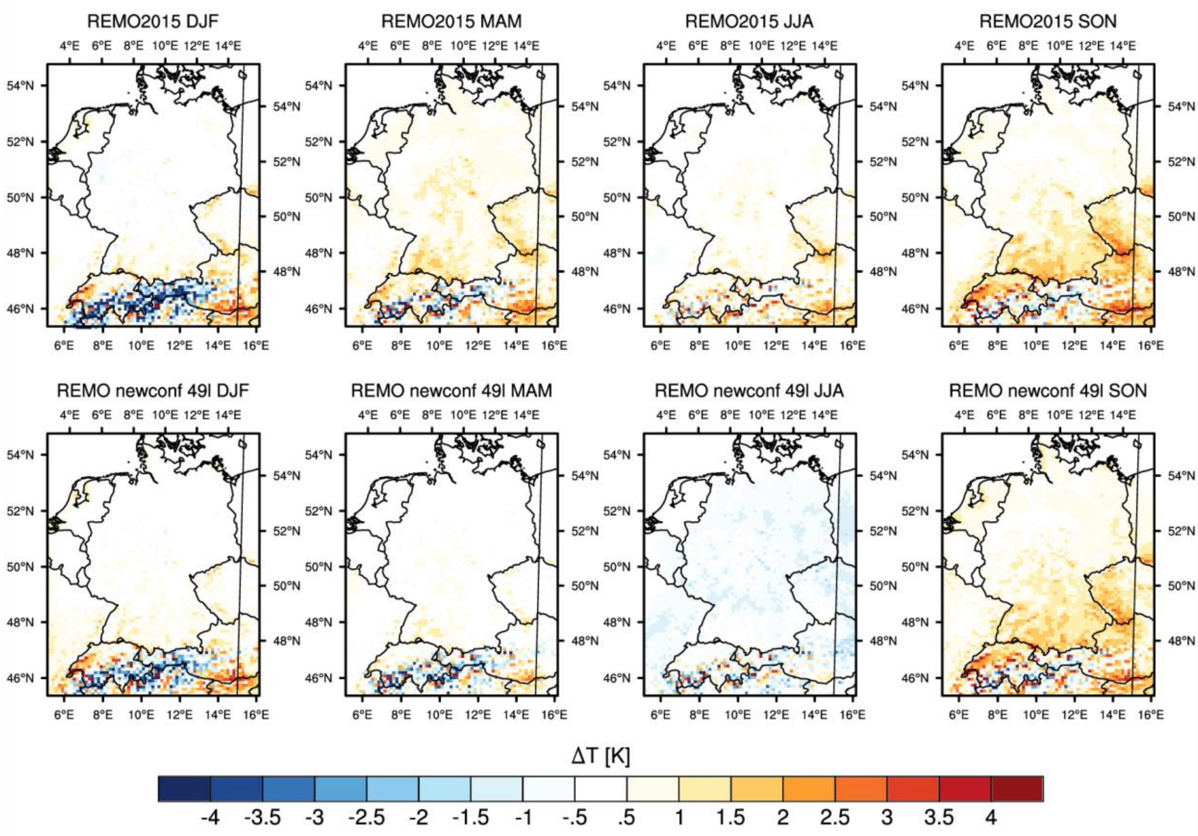

Fig. 2: Same as Figure 1, but for near-surface temperature in [K].

ICON-CLM and CCLM

In order to perform climate simulations with the ICON-CLM and CCLM model on MISTRAL, a runtime environment (SPICE - Starter Package for ICON-CLM Experiments) is used, which controls (i) the pre-processing of the boundary data (e.g. ERA5) being assimilated into the regional climate models, (ii) the configuration and execution of the climate simulations, (iii) the post-processing of the original model output for the partner in the NUKLEUS project and (iv) the archiving of the simulation results. The SPICE environment (developed by HZH) already existed for CCLM and therefore, had to be adapted for the ICON model and was extensively tested, especially the preprocessing. It was checked whether (i) the assimilation data were correctly assigned to the ICON-CLM grid and thus, to the respective land and water triangular cells and (ii) the missing input variables such as the soil moisture index were correctly calculated.

One example is given in Fig. 3 left showing the ERA-Interim reanalysis data from W_SO_REL (left panel – relative soil water content), which is used to calculate SMIL (soil moisture index) by considering the wilting point and field capacity of the respective soil type. Cells, which have a land portion of less than 50% according to the ICON-CLM grid, are at this point undefined. To solve this problem, the SMIL missing values are set to distance-weighted averaged values. In the following, the whole field is transformed on the ICON-CLM grid (Fig. 1 right panel) and is trimmed according to the land portion prescribed by the model. Thus, also cells having land portions less than 50% are considered. This is highly relevant for the tile approach being used in the ICON-CLM, which takes variations in surface types and related characteristics into account. With respect to the postprocessing, different cdo commands were tested to see, which one performs best in retransforming the ICON-CLM data on a regular grid (the internal re-gridding of ICON-CLM does not work for summed up and averaged quantities).

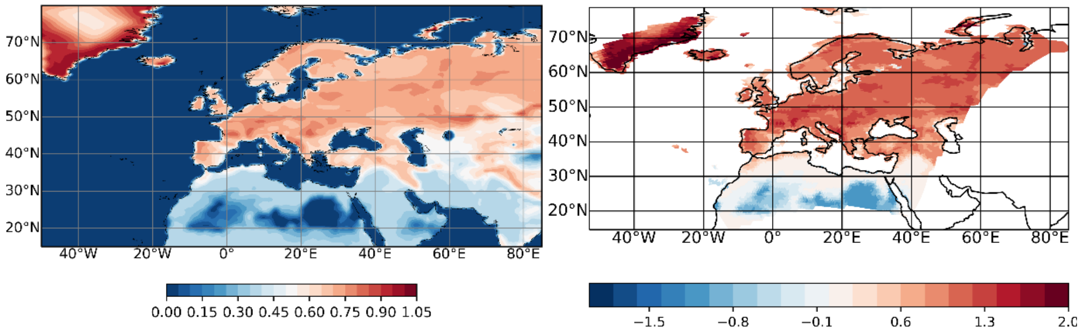

Fig. 3: W_SO_REL from ERA-Interim (left) and resulting SMIL transformed on ICON-CLM grid (right).

To be able to perform climate scenario simulations, the runtime environment had to be further developed. Currently, the ICON-CLM can only be driven by global ICON and IFS data as initial and boundary conditions, but ICON-CLM must have the possibility to be driven by different CMIP5/CMIP6 global climate models. An extra program had to be written to convert these data. Another big issue was the output of ICON-CLM, which had to be corrected to follow the CF-conventions.

Because the ICON-CLM is based on the ICON-NWP being usually used for the numerical weather prediction and therefore short-term simulations, several modifications were incorporated, e.g. (i) the time dependency of the greenhouse gases and sea surface temperature, (ii) the resetting as well as the summation and average of different quantities (water budget and radiation terms) over specified output intervals and more. In order to meet the demands of the NUKLEUS project, additional output quantities had to be added to the ICON model. The sunshine duration was introduced as a diagnostic quantity as well as the snow melting rate.

Owing to the further model developments, which have been introduced into the ICON-CLM also different errors arose. Problems with the e.g. Intel and GCC compiler were tried to fix also in collaboration with the contact persons from DKRZ and DWD. Therefore, test simulations with different configurations and modifications in the model code were performed to solve the problems as soon as possible.

Further test simulations with different versions of the CCLM model and with the modified ICON-CLM version were carried out on the MISTRAL for several years to see how they perform. One of the aims was to investigate the soil water balance to check whether the water cycle is disturbed. After implementing complex diagnostic procedures in CCLM as well as in ICON-CLM, several deficits were found in both models. In addition, the respective physical causes could be identified. The source codes of both models were improved accordingly and documented using the respective version management systems. The improvements to the models were checked in further control simulations. As an example, Fig. 4 shows the residuum of soil water content for the ICON release 2.6.3 standard version (left) and the improved model version ICON 2.6.3-clm3 (right). In standard ICON 2.6.3 release residua over larger areas appear with more than 100 mm/month, which is about 50% of precipitation. In contrast, the ICON 2.6.3-clm3 offers residua for the most part smaller than 1 mm/month (a few hot spots in mountainous regions reach 4 mm/month). This is a improvement by a factor of 100 and more.

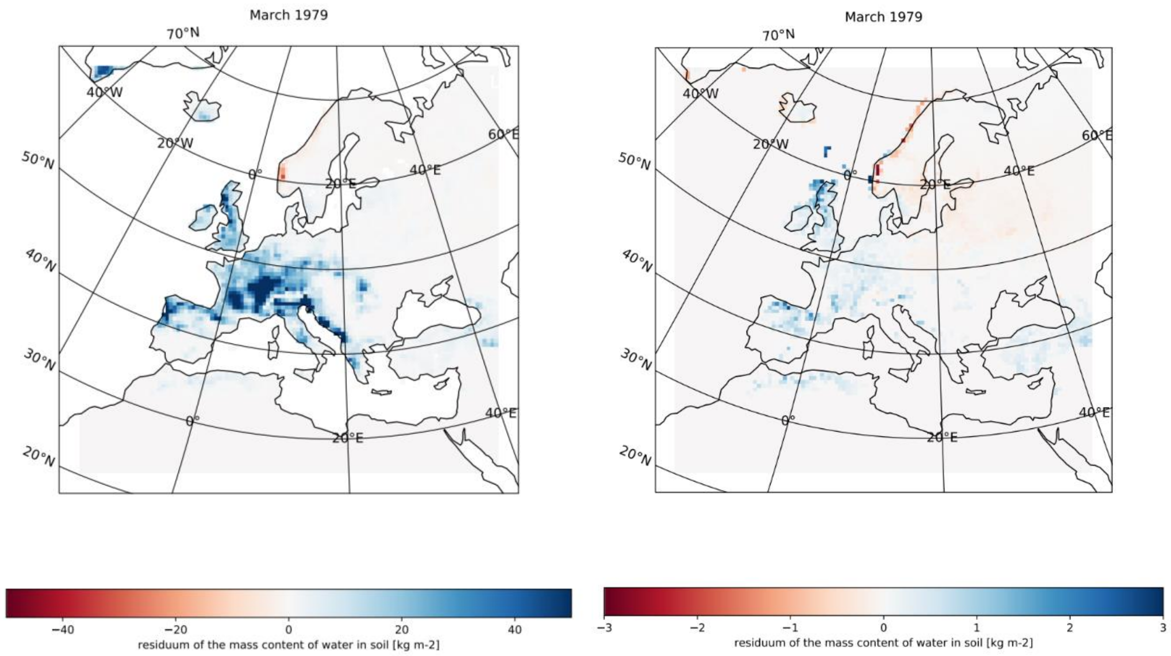

Figure 4: Simulation results for the residual in the soil water balance and for the month of March 1979 using the standard ICON release 2.6.3 (left) and the ICON 2.6.3-clm3 development version (right). The same is shown in the lower figures for the standard model ICON (left) and the improved ICON (right).

The test simulation also indicated that the climate simulations with the ICON-CLM are very CPU-intensive. However, the approved computing time on the DKRZ server is limited, so that a compromise must be found between computing time and the used resources. For this purpose, different test simulations have been performed on a 12 km grid to figure out under which conditions the experiments are either very fast and therefore, relatively expensive or slow and therefore, cost-effective. The number of MPI tasks and OpenMP threads was varied, and hyperthreading was switched on and off. Six test simulations are summarized in Table 1 along with the performance of 2 COSMO-CLM simulations. As the ICON-CLM simulation on a 3 km grid runs with a time step being four times smaller compared to the one for the ICON-CLM simulation on a 12 km grid, test simulations have been also performed with 3 km resolution to estimate the runtime.

Experiment	Partition	Nodes	Tasks per Node	Threads per Task	Hyper-threading	Time	Node hours
I1	compute	45	8	3	no	00h:37m:26	28
I2	compute	30	12	2	no	00h:53m:36	27
I3	compute	15	24	1	no	01h:41m:10	25
I4	compute2	30	12	6	yes	00h:41m:40	21
I5	compute2	20	18	4	yes	00h:59m:15	20
I6	compute2	10	36	2	yes	01h:51m:38	19
C1	compute	15	24	2*	no	02h:33m	39
C2	compute2	5	36	2*	no	05h:19m	27

Table 1: Test simulations for January 1979 with ICON-CLM (I1-I6) over 30 days on a 12 km grid to estimate the runtime and in the following, improve the performance on Mistral. Test simulations with COSMO-CLM (C1 and C2) done on nearly the same European domain (*: 2CPUs/task, time step 50% smaller than in the I1-I6 experiments).

Work Package AP2: Evaluation and Assessment

The tasks within this work package during the reporting period were (i) to contribute to the CMIP6 GCM selection process, (ii) to provide tailored climate change information to the

RegIKlim model regions based on the existing climate simulations at DKRZ and (iii) to test options for a bias correction.

GCM Selection

In total, three GCMs from the new CMIP6 ensemble will be downscaled to cover the uncertainty range of the climate change projections. The GCM selection is based on the following criteria:

- The required forcing data is available at the DKRZ node at ESGF.
- The GCMs meet the compiled selection criteria (incl. climate sensitivity, jet position) of the EURO-CORDEX community.
- The GCMs reproduce the weather in Europe well, especially with regard to the frequency/probability of occurrence of certain weather types and blocking. This ability is tested using the FREVA Plugins CWT and BLOCKING_2D.

On this basis, two GCMs have already been selected – MPI-ESM-HR and EC-Earth3-Veg.

Analysis of existing simulations from CORDEX and other projects

A comprehensive data collection of regional climate model (RCM) data from EURO-CORDEX CMIP5 simulations to complete the targeted ensemble matrix of 5 RCMS each driven by the same 5 GCMs was performed. The ensemble includes simulations of a historical period as well as the RCP8.5 scenario simulations for the 21st century until 2100.

In a second step, this 5x5 RCM ensemble was used for profound statistics of temperature and precipitation related quantities requested by the project partners (model regions) such as heat days, frost days, precipitation intensities and many others. These statistics were calculated for each ensemble member for the historical reference period of 1971-2000 as well as for two time periods in the scenario simulations, in particular, the near future period 2021-2050 and the end of century period 2071-2100. Afterwards, the single member statistics are combined to an ensemble statistic giving the ensemble mean and range. Aim of this part is to provide comprehensive and user-relevant climate fact sheets designed for the specific model regions of existing simulations, which will be updated by the new simulations later during the project phase.

Bias correction

In the third part some preliminary tests for a bias correction of temperature and precipitation have been performed for the smaller ISAP region using quantile mapping technique at which the modelled values are adjusted to observations using statistical probability density functions. For the future periods, some assumption such as stationarity of the model bias must be made. Nevertheless, a bias correction needs to be performed to ensure comparability of the different RCM-GCM realizations.

Data Management

To cater for a wide range of data analysis needs within the RegIKlim we set up an instance of the data analysis and search platform FREVA. Subsequently, we added reanalysis, observational and example model data to the data search engine. The example dataset at 3 km resolution is of special relevance as it provides the opportunity for project partners of the RegIKlim project to test their post-processing tools, like hydrological models. Before adding the mentioned datasets, the data was standardised for indexing in the FREVA data search engine. To do so, we developed a common data standardisation tool, based on the CMOR standard, which will also be used to standardise model output data produced in the next project stage.

Basic data analysis needs for most project participants were identified and plugins for application in FREVA were developed accordingly. Notable is a plugin to create and compare multi model ensembles and annular or diurnal cycles of those ensembles. We also modified the FREVA web part to display html-based plots enabling an interactive inspection of the results (see Fig. 5).

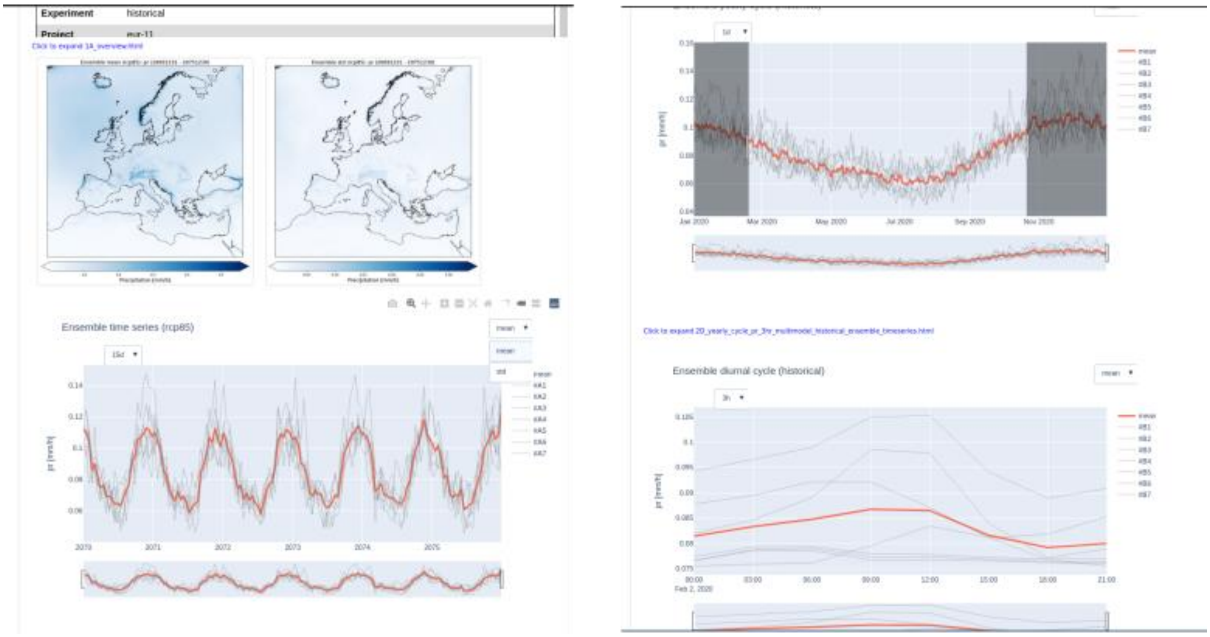

Fig. 5: Interactive html figures of a multi model ensemble comparison.

Additional value compared to other projects

NUKLEUS will downscale newly available CMIP6 global climate modelling simulations. The first downscaling step to the EUR-11 grid is a done in cooperation and as a contribution to EURO CORDEX (https://www.euro-cordex.net/; Jacob et al., 2020). The high-resolution simulations are performed in connection to projects like the BMBF research program ClimXtreme, the CORDEX FPS Convection, the EU project EUCP and the HAPPI initiative. The CCLM and ICON-CLM activities will contribute to and be supported by the CLM community (clm-community.eu/).

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