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

This is a follow-up 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 six 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

The first phase of NUKLEUS is extended to end of May 2023. A full proposal for a second phase, starting on 1st June 2023, was submitted in October 2022.

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) are applied within the project to cover the uncertainty range of the representation of regional scale processes – namely REMO (Jacob, 2001), COSMO-CLM (CCLM; Rockel et al., 2008) and ICON-CLM (van Pham et al., 2021). ICON-CLM is a newly developed regional climate model, derived from the ICON icosahedral nonhydrostatic model (Zängl et al., 2009) and has been applied for the first time to extensive climate change downscaling simulations.

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.

The GCM with CMIP6 global climate projections, which provide the required data for a dynamical downscaling have been analysed regarding their representation of European weather and climate pattern as well as the plausibility of their climate change signals. Three GCMs have been selected to cover the uncertainty range of these climate projections. The systematic selection process has been performed in collaboration with EURO-CORDEX[1]. NUKLEUS uses MPI-ESM-HR, EC-Earth3-Veg and MIROC6 simulations for the ssp370 scenario for the downscaling. The simulations are part of the next generation (EURO-CORDEX) CMIP6 regional ensemble.

The simulation process is ongoing and intended to be finished by the end of May (end of the extended phase 1 of NUKLEUS). Due to the delays and difficulties with the new HLRE4 system the planned simulations for 2022 can partly only be finished in 2023

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

Optimization and testing

REMO

An evaluation simulation of REMO2020 (a publication is currently being compiled) with ERA-5 forcing has been performed and results confirmed the superior behavior over REMO2015 of our test simulations in 2021. Due to many technical difficulties – often not within our control – the historical and scenario simulations with CMIP6 boundary conditions are lacking behind. As of fall 2022 only one historical simulation with MPI-ESM forcing has been finished.

ICON-CLM and CCLM

In order to perform climate simulations with the ICON-CLM and CCLM model on MISTRAL (until 05/2022) and LEVANTE (since 06/2022), a runtime environment (SPICE - Starter Package for ICON-CLM Experiments) is used. SPICE was adapted to the new supercomputer with its new node configuration, new archive system and new software architecture. Finally, SPICE for levanter allows for an automatic job-control starting from the preprocessing of

1 https://www.euro-cordex.net/

boundary / forcing data, going further to the preparation of model output for partners in NUKLEUS, and ending with the automatic archiving of model results (including examination of check sums). The adaptation to Levante was complicated by the fact that the machine and the archiving system was not reliable in operation (slurm-jobs cancelled, missing retrievals, downtimes, …).

To find an optimal setup for LEVANTE, scaling tests were done with the NWP version of ICON-CLM (June 2022) using a special CLM-wrapper allowing for bit-reproducibility and floating point trapping. The results show nearly perfect scalability over the various number of nodes used (Figure 1).

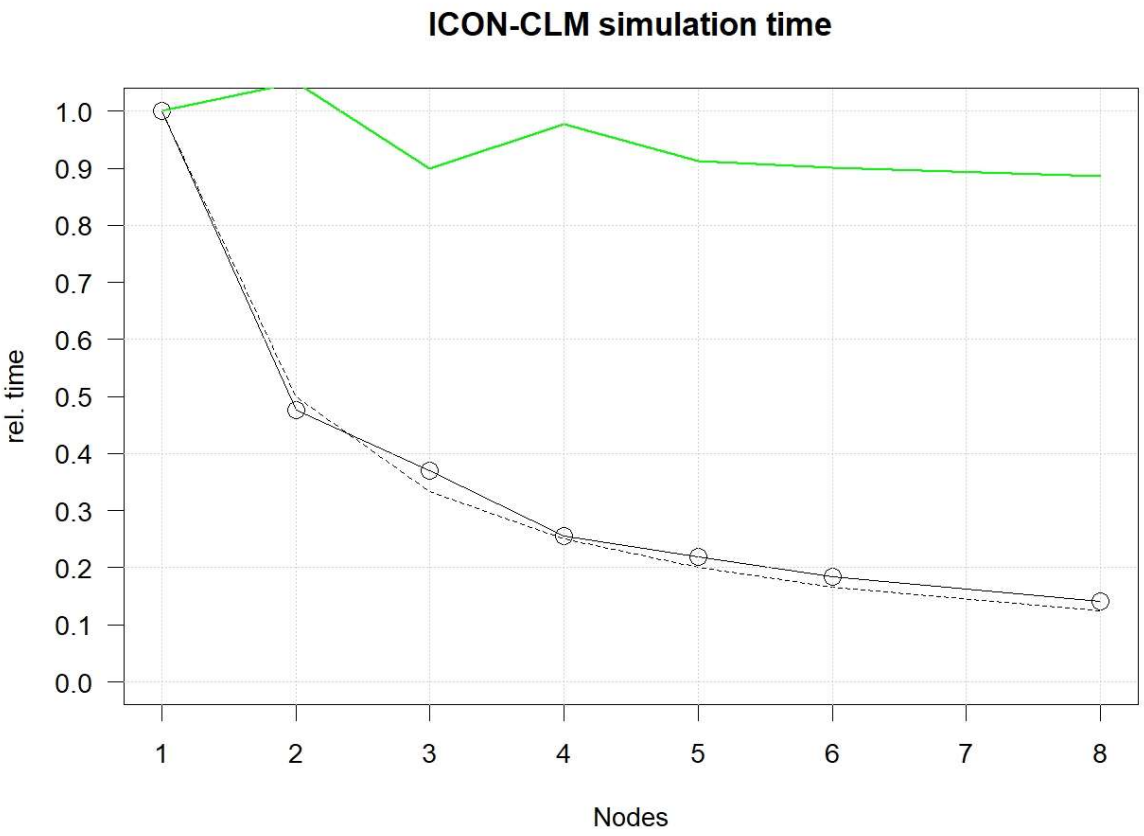

Figure 1: Scaling of ICON-CLM on LEVANTE from 1 to 8 nodes: solid grey line: observed; dotted line: theoretical curve; green line ratio observed/theoretical.

The CCLM benefits a lot from the new node configuration on Levante. As 128 CPUs are available per core, the same throughput as on MISTRAL can be managed on Levante but using only a quarter of nodes. Our experiments suggests that the communication over a large number of nodes and distributed memory is a bottleneck in the COSMO model and thus it is an advantage to use much more CPUs with the same number of cores. Table **Fehler! Textmarke nicht definiert.** summarizes the performance dependent on nodes for a climate-permitting convection simulation. The measurement incorporates 20 years of integration with different grid decomposition settings.

*Table **Fehler! Textmarke nicht definiert.**: Scaling test for COSMO-CLM for a simulation with 2.8 km nominal resolution. Measurement is for the average integration time for one month simulation.*

Nodes	Wall-clock time	CPU-hours	Node-hours
4	7.56	3875	30.3
6	4.81	3740	29.2
7	4.41	3950	30.85
9	3.30	3800	29.7

Assessment of the simulation quality

The NUKLEUS simulations for evaluation were already finished. As for REMO and COSMO new versions were applied and ICON-CLM was applied for the first time, also the model developers were highly interested in the performance of the simulations. The evaluation runs were performed on the EUR-11 CORDEX domain and on a 3km grid covering Germany and its adjacent regions.

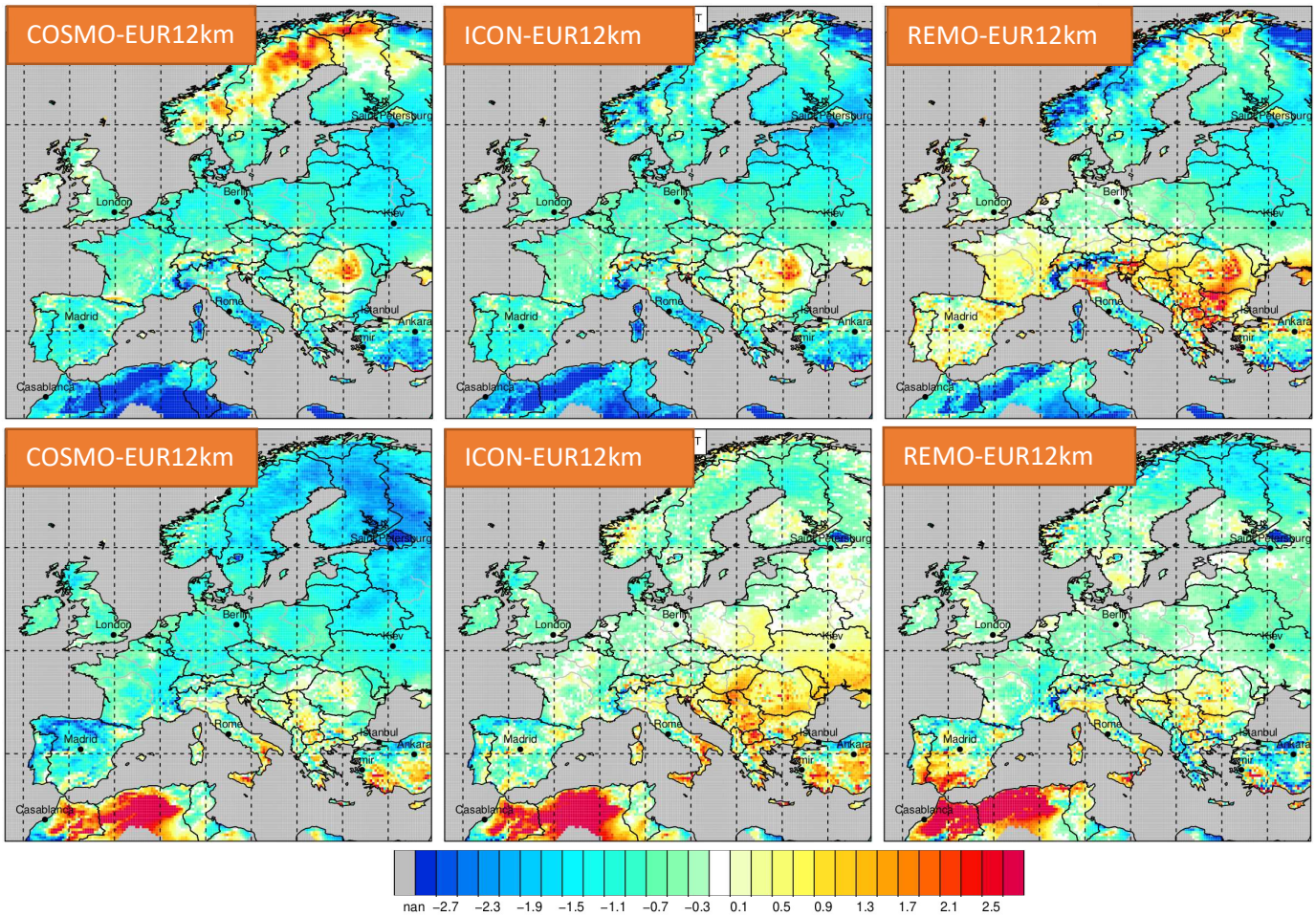

Figure 3: Bias of 2m mean temperature in winter (top) and summer (bottom) and with respect to the period 2001 to 2010. All models applied in NUKLEUS are shown. The reference data is taken from Eobs v24.

The BIAS for the mean temperature on the EUR-11 CORDEX domain is shown in Fig 3. ICON-CLM and COSMO-CLM are of similar quality. ICON-CLM offers smaller BIAS in Northern Scandinavian winter but lacks from warming in summer over Southeast Europe. The reason for a large-scale summerly cold BIAS in COSMO-EUR12 is the unintentional application of an

outdated physical parameterization. The REMO model lacks from a warm BIAS over Southeastern Europe in winter.

One of the ultimate goals of NUKLEUS is to provide users with high-resolution information for impact models and assessment of adaptation measures. Thus, the convection-permitting simulations were analyzed for their ability to better represent spatial and temporal variability of physical processes (as extreme precipitation). The daily cycle of precipitation is analyzed in Fig_2. The data show the mean over two of the NUKLEUS model regions: the Ruhr region

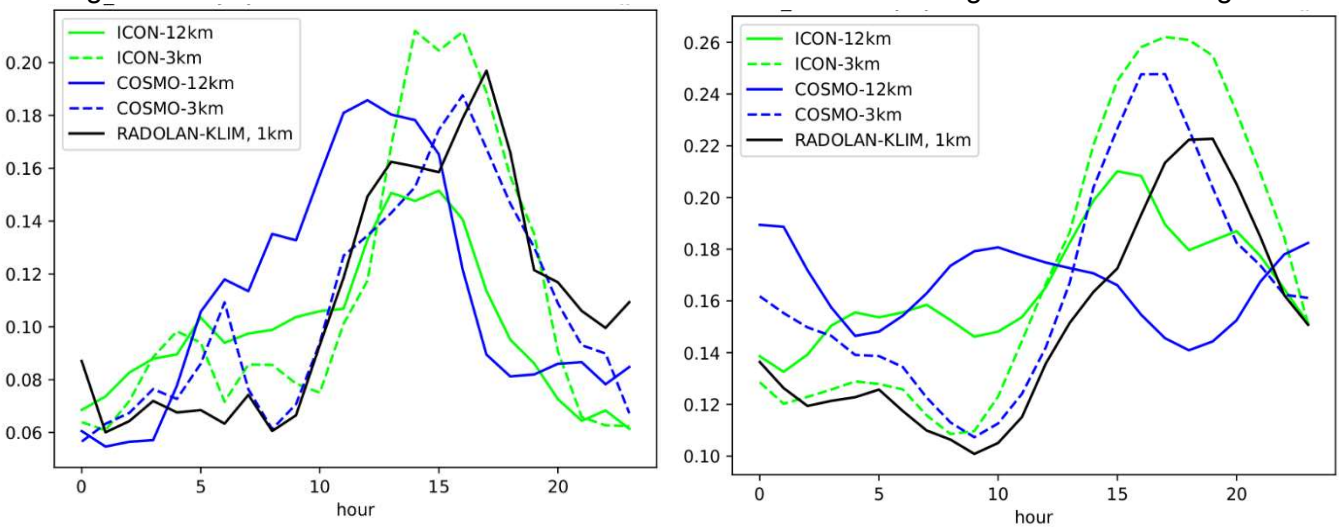

Figure 2: Daily cycle of precipitation for the summer seasons between 2005 and 2011. ICON-CLM is shown in green and COSMO-CLM is shown in blue. The domain of the Ruhr (Nordrhein-Westfalia) is shown on the left and the BON (northern Bavaria) is shown on the right. The reference data is the radar climatology of the Deutscher Wetterdienst with a resolution of 1 hour (RADOLAN-KLIM).

(left) and Northern Bavaria (right). Whereas the models with coarse resolution produce a lot of unrealistic precipitation in the morning and miss the correct timing (COSMO-12km is using another parameterization for deep convection than ICON-12km), ICON-3km and COSMO-3km correctly resolve low precipitation rates in the morning and a peak in the afternoon. However, the results also suggests that convection-permitting models tend to overestimate the high precipitation events (detailed analysis not shown here).

The added value of the 3km models become also evident for the spatial structure of precipitation. As the mountainous regions are much better resolved on high-resolution computational grid, ICON-3km and COSMO-3km much better resolve the reduced precipitation rates in the Elbtal south to Dresden (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Moreover, the sharp gradients of precipitation sums along the mountain ridges of the “Thüringer Wald” are better represented by ICON-3km and COSMO-3km compared to ICON-12km and COSMO-12km.

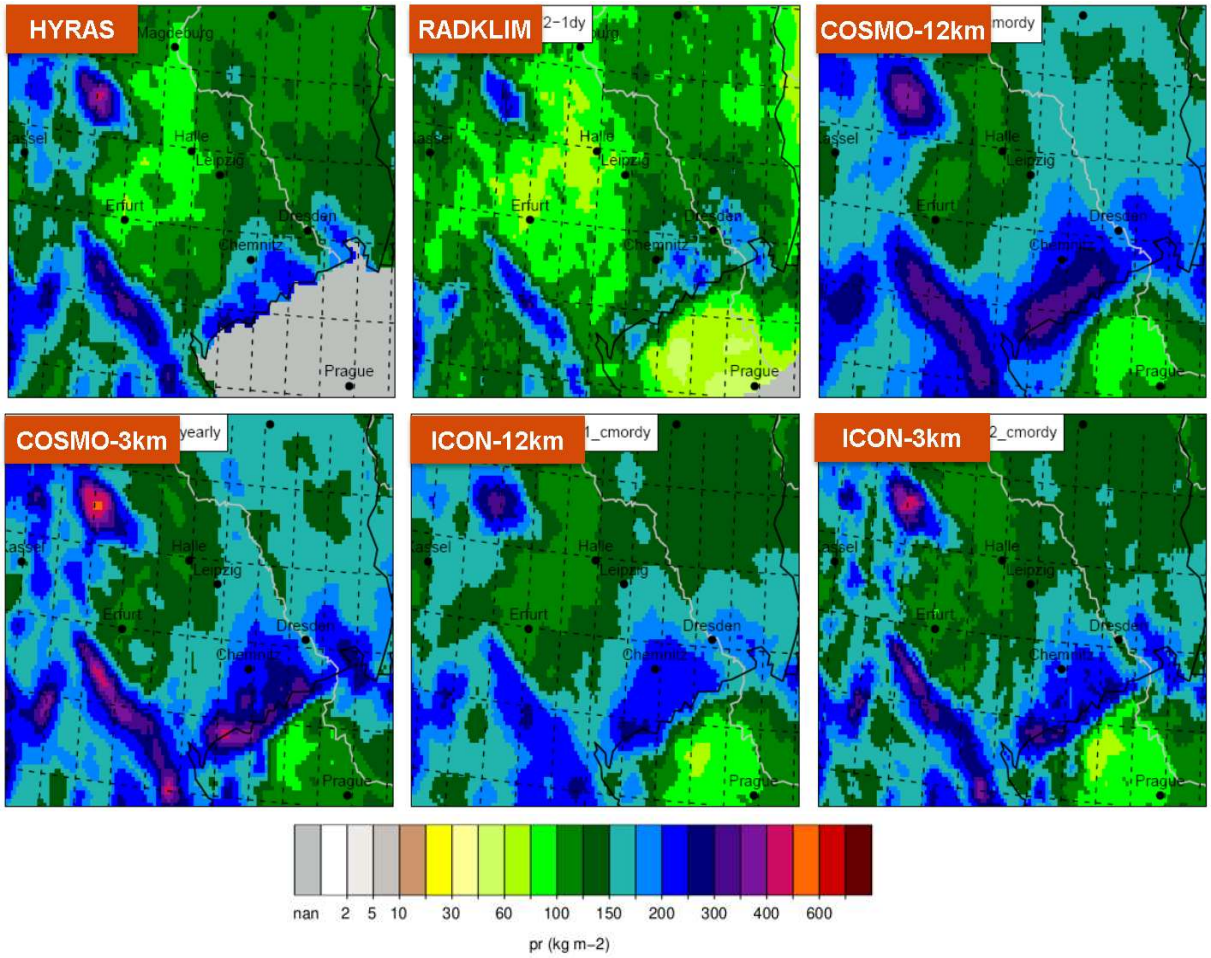

Figure 4: The winterly precipitation for Southeastern Germany and for the years 2005 to 2014. The reference data is HYRAS (Deutscher Wetterdienst). RADKLIM is the radar climatology.

Data Management

The ensemble of simulations will be made available to the project partners using the Freva platform. The standards for storing in FREVA are the same as for the ESGF archive: all the model results have to be transferred to the CMOR standards. Therefore, the tools for CMORization of ICON-, COSMO- and REMO-results were adapted to the new CORDEX standards for model output (https://cordex.org/wp-content/uploads/2018/11/CORDEX-CORE-Framework-final.docx) and to the CMIP6 metadata standards. In particular, 3-D variables need to be treated within CMORization.

Some of the NUKLEUS simulations were already integrated into the Freva platform and it is planned to add a lot of simulation until the end of the year 2022. However, it turned out that the reliability of the lustre storage system requires to backup the CMORized data to be able to quickly reproduce data for the NUKLEUS users in case of data losses.

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 (https://www-regiklim.dkrz.de). 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, a common data standardisation tool, based on the CMOR standard, has been adapted to the NULKLEUS simulations. It is intended to upload these CMORized data to the ESGF.

For the secund funding phase Freva will be extended as a backend for a climate change adaptation platform

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). Further Plug-ins will be incorporated in phase 2.

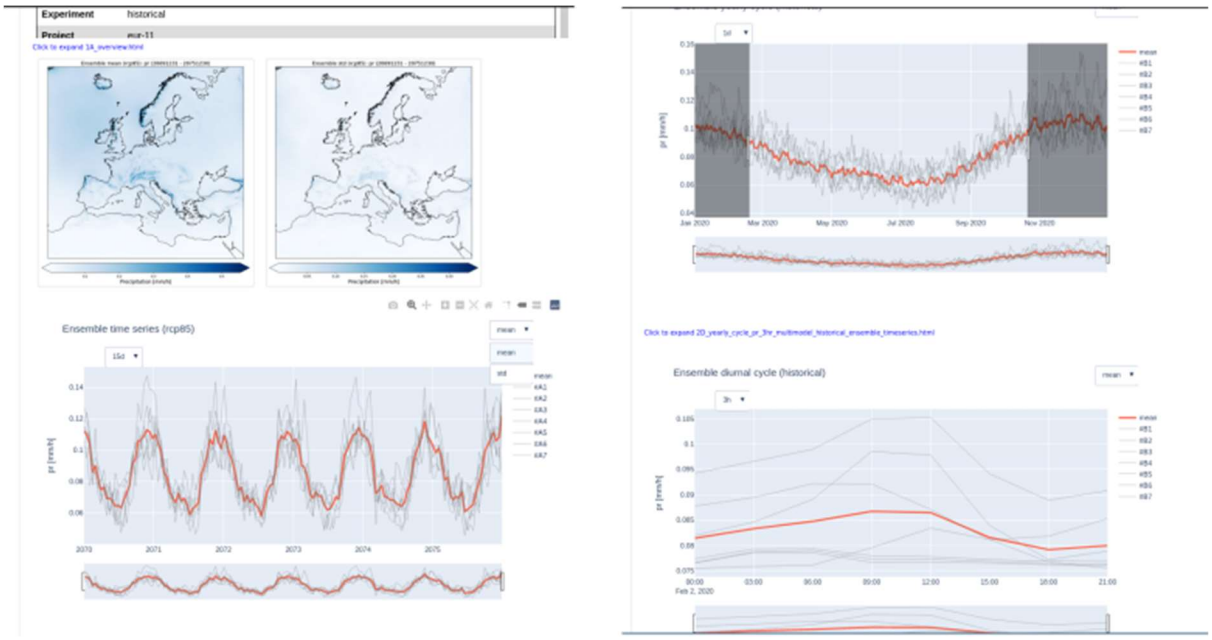

Fig. 5: Interactive html figures of a multi model ensemble comparison.

Resources used at DKRZ in 2022 (until October)

Compute time according to luv.dkrz.de

Table 2: Compute time used (Node-hours in 2022.

System	Period	Node-hours
MISTRAL	Jan - May	95.436
LEVANTE	May - Oct	117.339

Expired computing time on LEVANTE occurred to a large degree only in the first two quarters, when the machine was not yet available or not yet ready for production. The continuous workflow is still often hampered by downtimes, maintenance and the instability of the HSM system. The average consumption on LEVANTE is in Q3 and Q4 about 950 NH/day. On “trouble-free days” the consumption is about 2000 NH/day.

Workspace

The workspace (granted 479 TB) is currently 100% occupied.

The major part (>> 400 TB) is occupied by the time-series data already included or to be incorporated in Freva. The project urgently needs more workspace in 2023 to be able to give the participants access to the CMORized data via Freva as it is required within the project.

That leaves only a small fraction for the actual simulation workflow, which in principle is very efficient w.r.t. data overhead for input and raw output data. Especially, the forcing for high-resolution simulations is taken from the coarser scale EUR-11 simulations, which is retrieved from the archive and the raw model output is stored into the archive immediately after the first post-processing step. The whole process is severely hampered by the instability of the HSM system. It forces to keep more data on the workspace or to download the data for a period ahead, if possible, to reduce unproductive days, when the data can't be retrieved.

In the archive currently 1238 TB are already stored, increasing by about 20 TB/day.

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 WCRP CORDEX FPS Convection und FPS URB-RCC (URBan environments and Regional Climate Change) initiatives, and further research and application-oriented activities). The CCLM and ICON-LM activities will contribute to and be supported by the CLM community (clm-community.eu/)

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