Project: **1264**
Project title: **Storyline simulations of extreme events with spectral nudging**
Principal investigator: **Helge Gößling**
Report period: **2023-01-01 to 2023-10-31**

This report presents an overview of the completed and ongoing work employing the computational resources allocated in the ba1264 project. As outlined in the project proposal, the goal of this computing project has been to explore the storyline approach with unprecedented detail. To achieve this, we implemented a comprehensive workflow, where for the first time, the global nudging-based coupled-model storyline simulations with our CMIP6 model AWI Climate Model version 1 (AWI-CM1, ~100km grid spacing) for different warming scenarios (the range of available simulation has been extended in this project) have been downscaled with high resolution over Europe (12km grid spacing) and Germany (3km grid spacing). This allows us to study recent extreme events (like the 2022 European drought, heatwaves, or 2021 Germany floods) and the contribution of global warming to them.

In the proposal, we suggested various simulations with the AWI-CM3 model. However, the implementation of transient aerosol forcing in the atmospheric component of this model was delayed, and a simple first implementation does not yield convincing results. This prevented us from executing proper CMIP-type runs. Consequently, we decided to use only AWI-CM1 for the global simulations and to exclude AWI-CM3 from storyline production runs until reliable transient CMIP-type forcings are available. This decision, together with the late retrieval of the ERA5 data extending back to 1940 and storage constraints related to the underestimated amount of data from our previous simulations needed by the SCENIC project partners to run their models, explains a high proportion of HLRE-4 node hours expired in Q2 and Q3. However, we anticipate that this situation will not persist in the current quarter.

Thanks to the computational resources allocated this year, a wide variety of simulations have been produced.

1. *Global nudging-based coupled-model storyline simulations using AWI-CM1.*
   1a. The standard “Short nudged runs" (five ensemble members in different global warming scenarios starting in 2017 with 24 h e-folding time) have been extended until the end of 2022.
   1b. A new set of “Short nudged runs” with a stronger nudging configuration (1 h e-folding time) has started to be produced (present-climate available).
   1c. The previously available standard “Long nudged runs" (24 h e-folding time) have been extended until the end of 2022, along with conducting additional simulations. These new simulations can be categorized into two main groups. Firstly, we have completed the previously available standard runs to reach global warming targets of +2K, +3K, and +4K. Secondly, a new present-climate “long nudged run” with a stronger nudging configuration (1 h e-folding time) has been generated.
   1d. A new type of "long nudged run" composed of multiple shorter overlapping 5-years nudged runs for present climate has been generated
   1e. We conducted “perfect-model” type nudging simulations, wherein our model was run under pre-industrial climate conditions but with dynamics constrained (nudged) toward the end of the 21st century and vice versa. For each climate scenario, we ran four simulations: three following the standard nudging configuration (24 h e-folding time) and one employing a stronger nudging (1 h e-folding time). Each simulation covers 35 years.

2. *Dynamical downscaling of global nudged storylines with ICON-CLM*
   2a. Dynamical downscaling of the “short nudged runs” for all storylines (preindustrial, present, +2K, +3K, +4K) has been performed for the ensemble member 1 of the global AWI-CM1 data over Europe (12 km) and Germany (3 km), with the upper boundary nudging starting at 10500 m
   2b. After the analyses of the results from 2a, additional testing of the nudging configuration and global data interpolation had to be done
   2c. The influence of soil spin-up was tested, and a new spin-up strategy was developed
   2d. The dynamical downscaling from 2a has been repeated for Europe (12 km) with the new nudging configuration (nudging height 5000 m), bilinear interpolation of AWI-CM1 data, and additional spin-up year for PI, +2K, +3K, and +4K storylines.
   2e. A further dynamical downscaling (nesting) of the result from 2d to the German domain (3 km) has been performed for 11 simulation years out of 30, which will be completed in Q4 2023

2f. For the period from April to September 2019, all 5 AWI-CM1 ensemble members are planned to be dynamically downscaled in Q4 2023, at least over the European domain (12 km)

The main results can be summarized as follows:
The extension of our previous run has enabled us to apply our methodology, as outlined in Sánchez-Benítez et al. (2022) and Pithan et al. (2023), to investigate recent and record-shattering large-scale extreme events, like the summer 2022 heatwaves and drought in Europe or the Mediterranean heatwaves in 2022, and how they would unfold in different past and plausible future climates. Thanks to the workflow developed in this project phase, we are studying these events from a global perspective (using simulations from AWI-CM1), which allows us to find connections with fundamental teleconnection modes like ENSO and AMO.
In addition, taking advantage of the recently generated regional high-resolution simulations, the changes in the regional impact of these extreme events are currently being analyzed. This includes the addition of regional details to the study of the European heatwave in summer 2019 presented in Sánchez-Benítez et al. (2022), as well as quantifying the rate of the thermodynamic response of the land state over the extended drought period from 2018 to 2020, and during the drought of 2022. This workflow has led to several potential papers, some already submitted. However, it is worth noting that capturing very localized processes, particularly those associated with convective precipitation, such as the Ahr Flood in Germany in July 2021, remains a challenge within our current configurations.

Pithan et al. (2023) emphasize the importance of tailoring nudging parameters to the specific spatio-temporal characteristics of events. Consequently, we are using the new “Short nudged runs” with a stronger nudged configuration to better understand complex processes, like the warm and moist Arctic air masses intrusions (paper in preparation).

The utilisation of "Long nudged runs" allows us to analyse how observed variability (including, but not limited to, a broad range of similar extreme events) is replicated in our climate model. Flow-dependent biases or differential climate change influences are being analyzed (papers in preparation). The selection of an extended period is also better suited to properly spin up all aspects of the more slowly varying components, such as soil hydrology and subsurface ocean temperatures, so that they are brought into the correct phase of internal variability, which plays a pivotal role in the context of SCENIC project associated to this proposal. Another crucial aspect to consider involves calculating anomalies based on climatologies derived from these simulations, which may exhibit slight deviations from the free-run climatologies. Notably, we have observed a climate drift which is being part of a more in-depth analysis. To address this issue, we have started running a new series of simulations, composed of multiple shorter overlapping 5-years nudged runs. Until now, only the present-climate simulation has been generated and is currently being analyzed.

In this project phase, we conducted 'perfect-model' type nudging experiments to analyse the dynamic drivers of climate change from a novel perspective. Specifically, to maximise the signal-to-noise ratio in our analysis, we have chosen to focus on the two most extreme climate scenarios available, the pre-industrial climate and a +4K scenario.

In addition to our analyses, to reduce the storage requirements and to prepare the data generated from our simulations to be used by the SCENIC project partners for a range of applications, including dynamical downscaling, AI algorithms, and impact modelling, we have post-processed the data obtained from these simulations, which is now available in the work folder. However, during the proposal phase, we underestimated the amount of data the project partners would need for running their models. This has led to a lack of storage space in the work directory, which prevented us from running some of the additional planned simulations.

The resources assigned to our partners at GFZ Potsdam have not been utilized. They were intended for model development and tuning. Especially, the latter worked out much better than expected. The local compute servers at GFZ were in this case sufficient to fulfill the intended tasks.

References:
Pithan, F., et al.: Nudging allows direct evaluation of coupled climate models with in-situ observations: A case study from the MOSAiC expedition, Geosci. Model Dev., https://doi.org/10.5194/gmd-16-1857-2023, 2023
Sánchez-Benitez, A., et al.: The July 2019 European Heat Wave in a Warmer Climate: Storyline Scenarios with a Coupled Model Using Spectral Nudging, J. Climate, 35, 2373-2390, https://doi.org/10.1175/JCLI-D-21-0573.1, 2022.