Project: 1264
Project title: Storyline simulations of extreme events with spectral nudging
Principal investigator: Helge Gößling
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This computing project is associated with the Helmholtz Innovation-Pool project ACTUATE (climate Adaptation sCenarios To redUce the impActs of exTreme Events, 2025–2027, successor to SCENIC). We greatly acknowledge the continued support by DKRZ which is indispensable for the success of ACTUATE.

To summarize, continuing from the workflow established in the previous project phase, we have explored a hybrid pseudo-global warming (PGW)/storyline methodology. This involved running the ICON model for the EUR011 domain (12km resolution) and WRF, incorporating climate change increments derived from global nudged simulations. We have also continued updating the global storyline simulations in near-real time (see also climate-storylines.awi.de). Additionally, global "perfect-model" type simulations (nudging simulated winds from one climate to a different climate) have been the basis of a successful master thesis. Finally, simulations of this project have been used by several external partners to study impacts from a storyline perspective.

Simulations completed during this report period:

1. AWI-CM1, CMIP6 version:
    a. Extension of existing standard global “short runs” for the +2K and +3K climates to connect with the near-real time type experiments
    b. Extension of existing standard global “short runs” (5 climates: +0K, +1.4K, +2K, +3K and +4K climates) in near-real time (6 days delay)
    c. Additional “short runs” (weekly timescale) with stronger nudging (all vertical levels, all wave numbers, 1h timescale) branched off from the standard softly nudged simulations to analyze sensitivity to nudging parameters for selected events (e.g. Storm Boris in 2024 and Ahrtal floods in 2021)
    d. New idealised global nudging simulations ("perfect-model" type) with strong nudging extending for 35y in the four possible combinations (+0K/+4K climate combined with +0K/+4K winds).
2. Short ICON regional PGW-type simulations: Hybrid PGW/storyline approach focused on Ahrtal floods with 144 simulations (PGW/Storyline hybrid and standard PGW methods) covering combinations of ensemble members, warming levels (0K, +2K, +3K, +4K), perturbation types (thermo/dynamic), and initialization times (0, 6 and 12 hours before event onset), based on ERA5 initial/boundary conditions with perturbations derived from the global AWI-CM1 storylines. In addition, 90 PGW-type runs directly initialized from the global AWI-CM1 storylines, plus runs based on ERA5 with simplified uniform perturbations. Altogether, 450 simulations, each spanning 1–1.5 days.
3. Continuous 2018-2022 ICON regional storylines based on ERA5 with perturbations derived from AWI-CM1 storylines for pre-industrial, +2K, +3K, and +4K climates for AgraSim (see below).
4. Continuous 2018-2022 WRF regional storylines simulations including local-climate-zone enabled urban land model physics for two selected regions of Germany, with forcing derived from an AWI-CM1 -> ICON12km -> ICON3km downscaling chain.
5. For PALM-4U the set-up on Levante and creation of the static driver for PALM-4U have been completed successfully; test simulations planned for 2025-Q4.

Scientific results:

The “near-real-time” extension of AWI-CM1 storylines has allowed the analysis of a growing time span and rapid assessments, as exemplified earlier for the September 2024 floods in Central Europe (Athanase et al., 2024; see https://climate-storylines.awi.de/ for recent data). Papers investigating the recent record-low Antarctic sea ice and the recent European droughts are in preparation. Furthermore, the newly implemented "short runs" with strong nudging allow for the exploration of "what-if" scenarios where even small-scale and short-term motions, including in the boundary layer, can not adjust to the background climate. These efforts contribute to a report on Storm Boris where numerous European met-services and research groups collaborate. Finally, the perfect-model experiments have revealed that the thermodynamic climate change component largely dominates temperature

and precipitation responses, with dynamical changes modifying results significantly in some regions; this has led to a successful master thesis (Fig. 1) and a forthcoming paper.

We tested the novel ICON-based hybrid Storyline–Pseudo Global Warming (PGW) approach to estimate the extent of the July 2021 event under different warming levels. The analyses have been completed, and the manuscript is now nearing completion. As part of this work, the hybrid method was compared with approaches involving dynamical downscaling of standard smoothed delta-perturbation-based PGW, homogeneously perturbed PGW, and globally nudged simulations under the configurations described above. We discuss the potential benefits of the new method proposed for the literature by mainly focusing on the location and intensity of precipitation outputs, as well as the underlying drivers in both the initial and simulation states.

Based on the EUR-12 storylines, we conducted extensive research on the mechanisms of regional warming in summer associated with changes in the strength of the soil moisture-temperature coupling. A study entitled "Regional Nudged Storylines for the European Hot and Dry Summers 2018-2022: Response of Evapotranspiration Regimes to Climate Change," has been submitted to Climate Dynamics (see Fig. 1). As part of the collaboration with the AgraSim project (https://www.fz-juelich.de/de/ibg/ibg-3/expertise/forschungsplattformen/agrasim) in Jülich, we implemented a hybrid approach for the years 2018-2022 for pre-industrial, +2K, +3K, and +4K climates. This product is a combination of ERA5 reanalysis and ensemble-mean delta-fields computed based on the AWI-CM1 nudged storylines. The hybrid PGW-Storyline approach enhances the representation of precipitation over Western Germany, a crucial condition for applicability within the AgraSim facility. Starting from 2026, the data from these storylines is planned to be used as a basis for the climate input of the plant chambers.

When it comes to publications, we are maintaining the high level of productivity since the SCENIC project (https://earthenvironment.helmholtz.de/changing-earth/innopool-projects/scenic/). In 2025, we successfully published papers analyzing the European summer heatwave of 2019 from a regional perspective (Klimiuk et al., 2025), the vulnerability of European agriculture to increased heat stress (Martin et al., 2025), and an attribution analysis of climate change's impact on the cold extremes of East Asia in 2020/21 (Zhuo et al., 2025). Currently, we have a paper under review that examines the intensification of multi-year droughts (Ketaren et al., submitted to Earth's Future) another validating nudged CMIP6 models in the Arctic (Trivedi et al., submitted to Frontiers in Earth Sciences), and numerous more papers in various stages of review or preparation.

This wide range of applications and collaborations has required extensive post-processing and data storage, which was made possible through the resources granted in this project. While the extensive post-processing, data storage requirements and project deliverables initially led to expired resources in the first and third quarter, all granted node hours were used in the second quarter, and this trend is expected to continue in the future. However, due to the significant reduction in HLRE-4 node hours and disk space, we were unable to complete some planned simulations, such as the "new long nudged runs."

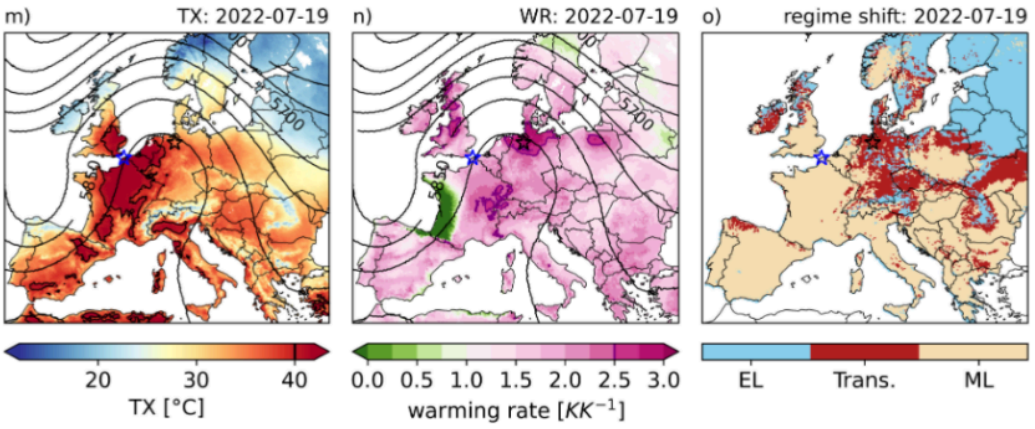

Figure 1. Figure 10 from Klimiuk et al., submitted. Present-day maximum 2m temperature reproduced by our storyline (AWI-CM1 downscaled with ICON) simulations (left), warming rates (middle, in K per K of global warming) and regime transitions from Energy limited to Moisture limited due to climate change (right).