Project: 1264
Project title: Storyline simulations of extreme events with spectral nudging
Principal investigator: Helge Gößling
Report period: 2025-11-01 to 2026-10-31

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) and, since October 2026, with the EU Horizon project SUNRISE (Extreme Events in a Warming, Unequal World: Linking Drivers to Impacts for Improved Attribution, Forecasting and Regional Responses). We gratefully acknowledge the continued support of DKRZ, which is indispensable for the success of both projects.

To summarize, we have continued updating the global AWI-CM1 storylines in near-real-time (climate-storylines.awi.de), performed the first “nudging-stopped” simulations and produced new +2.5K and +3.5K storylines for the AgraSim platform at Forschungszentrum Jülich. At the regional and urban scales, the ICON-CLM storylines were substantially extended and first PALM-4U simulations were carried out. Due to delays in the CMIP7 FastTrack simulations of the CAP7 project, except for short technical tests with a CMIP7-like version to ensure that the nudging works, the planned AWI-CM3 storyline simulations have been moved to end-2026 and, if the follow-on proposal succeeds, 2027.

**Simulations performed during this report period:**

1. AWI-CM1, CMIP6 version:
    a. Near-real-time extension of the standard global “short runs” (five members; pre-industrial, +1.4K, +2K, +3K and +4K). Due to technical issues with the restart files, the extension is currently performed monthly instead of daily.
    b. New “nudging-stopped” simulations (free-running ensembles from slightly perturbed states after a strongly nudged spin-up): (i) four atmospheric blocking events in the pre-industrial, present-day and +4K climates (25 members, with the nudging stopped just before the onset of each event), and (ii) first exploratory simulations for the summer of 2026 in Europe (present-day climate).
    c. New “short runs” (five members, 2017–2022; to be completed by the end of 2026) for +2.5K and +3.5K to derive climate change increments for the AgraSim plant chamber experiments.
    d. Correction of some existing simulations.
2. AWI-CM3, CMIP7-like version:
    a. Successful short technical tests to ensure that the nudging works as expected.
3. Regional ICON-CLM (five climates):
    a. “Classical” storylines (dynamical downscaling of the AWI-CM1 storylines) extended until the end of 2024 (members 1–5) and July 2026 (member 1).
    b. Hybrid storylines (ERA5 plus AWI-CM1 storylines increments) extended to 2015–2022 for all climates, including new pre-industrial runs (extended until the end of 2024), and ICON control run extended until July 2026.
    c. Correction of some existing simulations.
4. PALM-4U (version 25.10): present-day and warmer climates, including urban greening scenarios, for a neighbourhood in Karlsruhe, driven by 3 km ICON simulations (20 m parent and 5 m child domains).

**Selected scientific results:**

The near-real-time storylines enabled rapid analyses of the exceptionally warm and dry spring and summer of 2026 in Europe, including the low river levels (Kettaren et al., 2026b, preprint), and form the basis of a paper analysing their impacts at different scales with the full ACTUATE modelling chain (Klimiuk et al., in preparation). Our storylines of Storm Boris showed that, without anthropogenic climate change, precipitation would have been 6–9% lower (Athanase et al., 2024b); hydrological simulations driven by them show that flood peaks would have been even 14–22% lower on average, owing to the non-linear runoff response (Miersch et al., 2026; Fig. 1).

The nudging-stopped simulations probe how the dynamics of specific extreme events, prescribed in the standard storylines, respond to the climate background. A first application to atmospheric blocking (Zhuo et al., to be submitted) shows that the characteristics of the blocks remain largely unchanged across climates, except in one case, reinforcing the usefulness of the standard storyline approach. This approach is now being applied to the

summer of 2026 in a new collaboration with Wageningen University & Research and will be further pursued in SUNRISE.

The regional storylines are used by other consortium partners to drive land-surface and impact models. The hybrid storylines represent precipitation better than the “classical” ones, for example reducing a wet bias over Western Germany, a crucial condition for their use as climate input for the AgraSim plant chambers, where a first experiment using our 2017 data is ongoing. To provide a finer sampling of warming levels for further experiments, new global +2.5K and +3.5K storylines are produced this year, from which the corresponding regional storylines will be derived in 2027.

At the urban scale, a sensitivity analysis with PALM-4U allowed us to optimise the simulation length for testing to 24 hours, while the final scenario simulations will cover 72 hours (three diurnal cycles). Preliminary results show the impacts of future warming and urban greening on local thermal conditions in Karlsruhe.

**Publications and collaborations:**
In 2026, papers were published or accepted on multiyear droughts (Kettaren et al., 2026a), evapotranspiration regimes and warming amplification (Klimiuk et al., 2026), floods (Miersch et al., 2026), whiplash events (Merz et al., 2026) and model evaluation in the Arctic (Trivedi et al., 2026), and preprints were released on European droughts (Sánchez-Benítez et al., 2026) and low river levels (Kettaren et al., 2026b). Further papers are submitted or in preparation on compound hot and dry events (Yadav et al., submitted), atmospheric blocking (Zhuo et al.), the summer of 2026 (Klimiuk et al.), Antarctic sea ice (Lyu et al.), the Ahrtal floods (Ludwig et al.), the relative roles of thermodynamic and dynamic changes (Monfort et al.), marine heatwaves (Athanase et al.), North Atlantic storms (Pinto et al.), renewable energy (Meng et al.) and the flow-dependent climate change response (Sánchez-Benítez et al.). The simulations also contribute to a multi-institutional report on Storm Boris. Beyond the ACTUATE and SUNRISE consortia, the data are used by a broad network of partners in Germany and abroad. Full references and partners are given in the current and previous proposals.

**Resource usage:**
The granted resources were largely used for the near-real-time extensions, the nudging-stopped experiments, the regional and urban simulations, and the extensive post-processing and data storage required by our partners. However, the delays in CAP7 prevented the AWI-CM3 simulations, which accounted for a large part of the request, except for successful technical tests; together with storage limitations, this led to some node hours expiring. Some of the node hours planned for the AWI-CM3 storylines were therefore transferred to CAP7 to support the CMIP7 FastTrack simulations, whose restart files are the starting point for our AWI-CM3 storylines and thus essential for this project. The CAP7 delay also enabled important unplanned simulations, namely the new +2.5K and +3.5K storylines for AgraSim. In addition, the system outages and the recent high machine load delayed several of our simulations and partly contributed to the expiry of node hours. The long-term archive has not yet been used either, as the transfer of the AWI-CM1 data is linked to the new AWI-CM3 simulations and has been postponed accordingly.

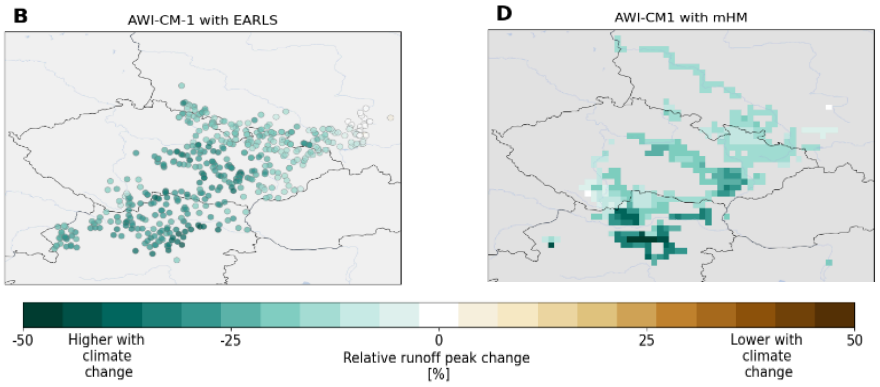



*Figure 1.* Just published in *Science Advances*: Climate change amplified the flood peaks of Storm Boris (September 2024) non-linearly, i.e. more than precipitation. Relative change in flood peaks in pre-industrial compared with present-day hydrological simulations driven by the AWI-CM1 storylines, at gauging stations (EARLS; left) and grid cells (mHM; right) above the 25-year return period. Adapted from Miersch et al. (2026).