Usage Report of DKRZ Resources

Project: bb1152 ClimXtreme (subproject bm1159)

Project title: ClimXtreme: Climate Change and Extremes (ClimXtreme)

Project leader: P. Friederichs, J Pinto, U. Ulbrich, F. Kaspar

Project Funding: BMFTR

Reporting period: 05/2025 – 10/2025

Table 1: Used resources at DKRZ (by end of October 2025) in project bb1152 (and subproject bm1159).

Resource bb1152	Granted	Utilization	Remaining
Levante CPU nodes (Node hours)	45854	29497	16357
Levante GPU nodes (Node hours)	3547	2060	1487
Levante Storage (TiB)	405	381	24
Archive project (TiB)	766 (thereof 315 purchased)	203	563 (thereof 315 purchased)
Archive long term (TiB)	2	412	-410
Resource bm1159	Granted	Utilization	Remaining
Levante CPU nodes (Node hours)	6720	6689	31
Levante GPU nodes (Node hours)	3700	3212	488
Levante Storage (TiB)	380	353	27
Archive project (TiB)	0	-38	38
Archive long term (TiB)	0	0	0

Scientific activities conducted during the report time

1. Module A – A1 SEVERE

Subproject: A1: Scale Dependent Process Representation and Sensitivity Analysis for Most Extreme Events

Subproject leader: Hendrik Feldmann, Joaquim G. Pinto, Institute of Meteorology and Climate Research (IMK-TRO), Karlsruhe Institute for Technology (KIT), Karlsruhe

1.1 Usage report May 2025 – October 2025

Main focus during the reporting period was the assessment of the climate change signal for extreme precipitation for short intense events. Hundhausen et al. (2025) evaluated the representation of sub-hourly event profiles from kilometre-scale climate simulations with station and radar data (cf. Figure 1). It was concluded that the model simulations were in the range of the observational references. Thus, the model data are able to provide valuable information to account for climate change effects on (flash-) flood risks.

An additional study used such kilometre-scale simulation as drivers for hydrological models to calculate local flood risk maps (Laux et al., 2025).

Some resources were used for the bias adjustment and homogenization of the available CMIP5/CMIP6 EURO-CORDEX simulations under various emission scenarios, to assess the rate of increase in extreme precipitation intensities depending on the global warming level analogue to Hundhausen et al. (2024). The data are also used for the assessment of fire weather potential under climate change.

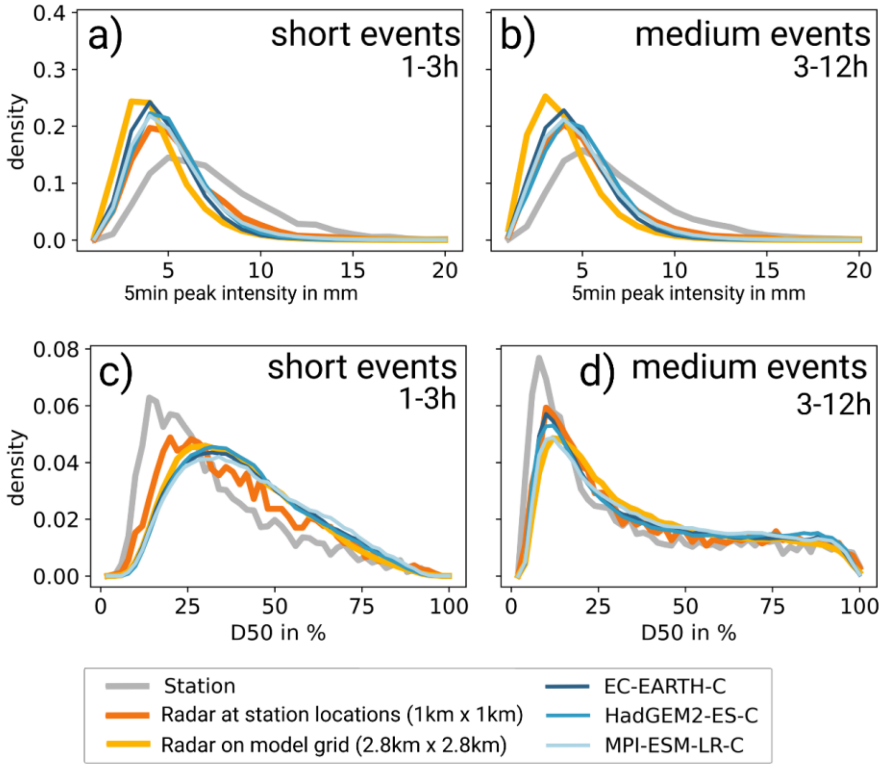

Figure 1: Maximum 5-min intensity (first row) and D50 ((percentage of event time until 50% of the precipitation occurred; second row) for 1 h annual maximum generating events of different duration categories of short-duration (first column) and medium-duration (second column) events (from Feldmann et al., 2025).

1.2 Project related publications:

Hundhausen M., Feldmann H., Kohlhepp R., and Pinto J.G. Climate change signals of extreme precipitation return levels for germany in a transient convection permitting simulation ensemble. *Int. J. of. Climatol.*, 44(5):1454–1471, https://doi.org/10.1002/joc.8393, 2024.

Hundhausen M., Fowler H.J., Feldmann H., and Pinto J.G.: Sub-hourly precipitation and rainstorm event profiles in a convection-permitting multi-GCM ensemble. Weather and Climate Extremes, 48:100764, https://doi.org/10.1016/j.wace.2025.100764, 2025.

Feldmann, H., Hundhausen, M., Churiulin, E., Cusinato, E., Bohmann, M., Ludwig, P. and Pinto. J.G. Updating climate change simulations for Europe and Germany, Book Chapter, in: High Performance Computing in Science and Engineering 24 Transactions of the High-Performance Computing Center Stuttgart, accepted.

Laux, P., Feldmann. D., Marra, F., Feldmann, H., Kunstmann, H., Trachte, K., Peleg, N.: Future precipitation extremes and urban flood risk assessment using a non-stationery and convection-permitting climate-hydrodynamic modeling framework. Journal of Hydrology, https://doi.org/10.1016/j.jhydrol.2025.133607, 2025.

2. Module A – A5 DesAttHeat

Subproject: A5: The role of multi-scale dynamical processes in shaping recent and future extreme heat waves over Germany

Subproject leader: Alexander Lemburg[1], Joaquim G. Pinto[1], Andreas Fink[1], Dalena León Fon Fay[2], Frauke Feser[2]

1) Institute of Meteorology and Climate Research - Tropospheric Research (IMKTRO), Karlsruhe Institute for Technology (KIT), Karlsruhe

2) Institute of Coastal Systems Helmholtz-Zentrum Hereon, Geestacht

2.1 Usage report May 2025 – October 2025

As mentioned in the previous report, in work package 1 (WP1, KIT) of A5 we investigate differences between heatwaves that are associated with an Omega blocking and those linked to subtropical ridges, which are projected to play a greater role in a future climate. During the reporting period, the focus was on submitting and currently revising a publication about the Lagrangian analysis of Central European heatwaves in today's climate, exploring heat-generating processes and their differences between ridge- and Omega-type heatwaves. Using highly-resolved ERA5 data, we computed backward trajectories with Lagranto for the respective 20 most textbook-like heatwave cases of both circulation type in the time period 1950-2023. By applying a Lagrangian temperature decomposition algorithm (Röthlisberger & Papritz, 2023), temperature anomalies of air parcels reaching the heatwave region could be attributed to the processes of advection, adiabatic heating and diabatic heating. The main results of our study are summarized schematically in Figure 2. Omega heatwaves are characterized by the fact that diabatic heating from the surface plays a significantly greater role than in heatwaves associated with a ridge, especially 2 to 3 days after the start of the heatwave. On the other hand, warm air advection does not contribute to Omega-type heatwaves. In addition to an actual small positive contribution from advection, warm air anomalies in ridge-type heat waves can be explained in particular by adiabatic warming due to subsidence, especially a few days after the onset.

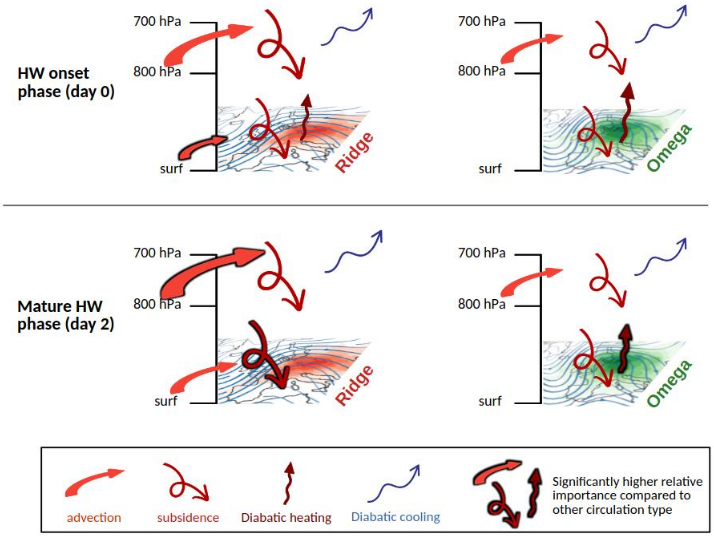

Figure 2: Schematic representation of the most important results of this study. The top row shows a comparison of the relative importance of the processes (i.e., advection, adiabatic heating and diabatic heating) between Omega- and ridge-type heat waves both for the initial phase (top row) and for a later point in time of the heat wave (bottom row). The relative size of the arrows representing the respective processes shows the relative importance of these processes, for both air masses near the surface and air masses just above the boundary layer. Significantly higher relative importance compared to the other circulation type is indicated by shading around the respective arrow.

In work package 2 (WP2, Hereon) of A5, the spectrally nudged storyline approach (van Garderen et al., 2021) is used to perform physical attribution of an extreme event of the recent past by comparing storylines of the same event representing its development in a Counter Factual (pre-industrial conditions), Factual (present conditions) and Plus xK degrees of global warming (future degrees of global warming with respect to preindustrial times). The storylines differ only in sea surface temperature and greenhouse gases, as these are variables that were strongly impacted by human activities. In addition, spectral nudging is applied which takes care that large-scale weather patterns of the model stay close to reanalysis data, so that historic extreme events of large impact can be re-simulated for the different climate states of the storylines. In previous studies, global storylines simulated with ECHAM6 (Res. T255) have been used by our group, for instance in the study of the 2022 European heatwave

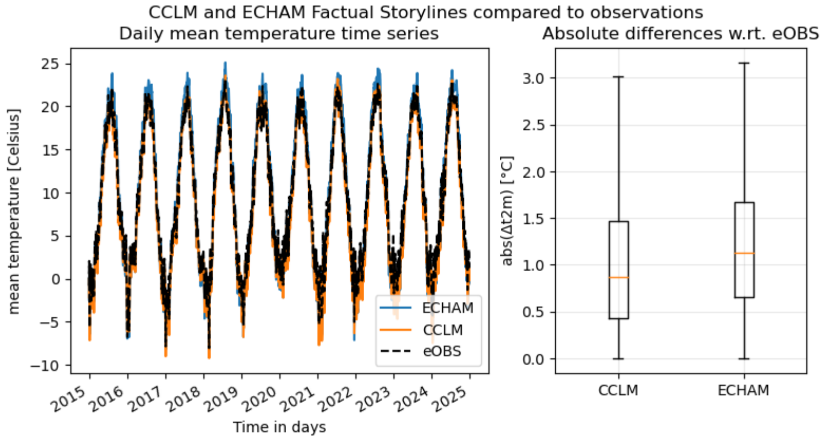

Figure 3: a) CCLM and ECHAM daily mean temperature compared eOBS. b) Absolute daily mean temperature differences between regional and global storylines with respect to eOBS.

(Feser, 2024), and a combined conditional attribution methodology developed within DesAttHeat for the quantification of the role of global warming from a storyline-statistical perspective (León-FonFay, under review).

In the second stage of the project, regional storylines are simulated by downscaling the global storylines to the EURO-CORDEX region by using COSMO-CLM. The new storylines are now closer to observation data (eOBS) (Figure 3). Therefore, we are currently in the process of simulating the COSMO-CLM storylines for the same levels of global warming as the global storylines (Counter Factual, Factual, +2K, +3K, +4K) for the EURO-CORDEX region (Res 0.11°) and the time period of 2015 to present, counting on 3 members per storyline. The 3 members per storyline will provide mini-storyline-ensembles and will be run with slightly different starting conditions to check the robustness of the attribution results. These simulations will allow us to have an improved representation of physical systems over Europe and a better representation of extreme events, extending our research from heat-related events like heatwaves to other extreme events that require higher resolution like precipitation extremes (Figure 4).

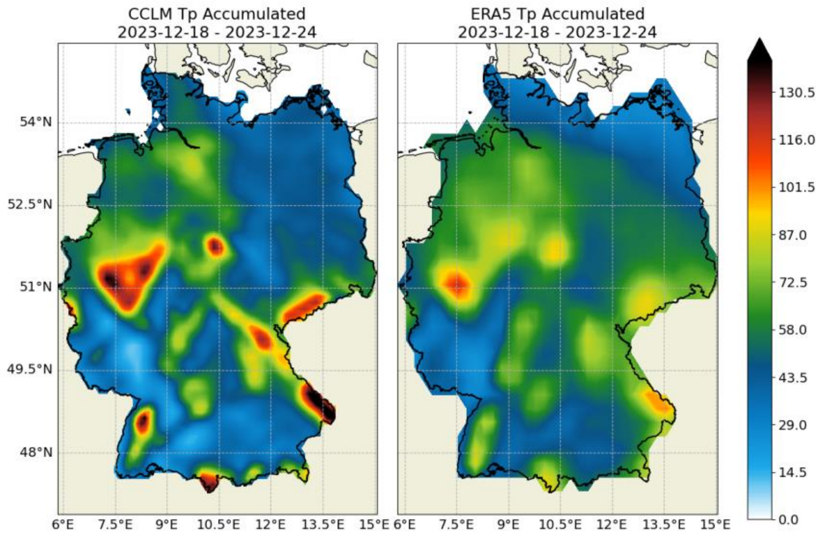

Figure 4: a) CCLM Simulated Total precipitation compared to b) observed total precipitation in ERA5 for 18-12-2023 to 24-12-2023

2.2 Project related publications:

van Garderen, L., Feser, F., Shepherd, T. G., 2021: A Methodology for Attributing the Role of Climate Change in Extreme Events: A Global Spectrally Nudged Storyline. Natural Hazards and Earth System Sciences, 21, 171-186, 2021, https://doi.org/10.5194/nhess-21-171-2021.

Feser, F., van Garderen, L. and Hansen, F., 2024: The summer heatwave 2022 over Western Europe: An attribution to anthropogenic climate change. Explaining Extreme Events of 2022/2023 from a Climate Perspective, Bull. Amer. Meteor. Soc., 105, 11, https://doi.org/10.1175/BAMS-D-24-0017.1.

León-FonFay D., Lemburg A., Fink A.H., Pinto J.G., Feser F., 2025 A combined storyline-statistical approach for conditional extreme event attribution. Weather and Climate Dynamics (under review)

3. Module A – A6 CyclEx

Subproject: A6: Intensity and structural changes of extreme mid-latitude cyclones change in a warming climate

Subproject leader: Svenja Christ, Pinto Joaquim G. Pinto, Julian Quinting
Institute of Meteorology and Climate Research – Tropospheric Research (IMK-TRO), Karlsruhe Institute for Technology (KIT), Karlsruhe

3.1 Usage report May 2025 – October 2025

CyclEx investigates the changes in the intensities and frequencies of extreme mid-latitude cyclones in a warming climate and uncertainties related with the representation of diabatic processes. Followed up on the work of idealized baroclinic life cycles in the ClimXtreme A6 project Phase 1, for Phase 2, we plan first to (1) identify the most extreme observed windstorms in ERA5 and high resolution MPI-GE global climate model simulations using the ZYKPAK plug-in on the Freva analysis platform and to (2) carry out pseudo-climate warming simulations with ICON-CLM. In addition to the pressure tendency equation (PTE) analysis (Fink et al., 2012), we will use the EuLerian Identification of ascending Air Streams (ELIAS) approach (Quinting et al. 2022, Quinting and Grams 2022) for the quantification of diabatic processes to study the possible scale dependency of the relevant physical processes on extreme cyclones.

Dr. Ting-Chen Chen, who has left the project end of 2023, published a paper in on the results of Phase 1 in the report period on the idealized ICON simulations.

Since the start of Svenja Christ in the project in February 2024 the first part of the planed project was started and cyclone tracks of ERA5 were selected and further analyzed with the PTE and the ELIAS approach. Additionally, cyclone composites were generated and analyzed. The main preliminary result is that the separation with the help of the PTE approach into diabatically and baroclinically driven cyclones shows structural differences of their position (Figure 5) and features, like surface wind, precipitation, and warm conveyor belts (WCBs). Diabatically driven cyclones are associated with more precipitation, stronger surface winds and more WCBs.

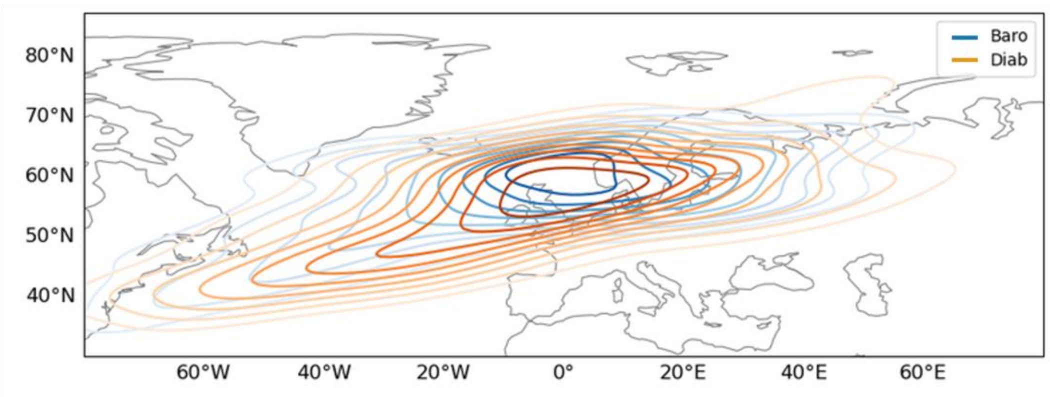

Figure 5: Cyclone Density of extreme ERA5 extended winter windstorms impacting central Europe, orange diabatically and blue baroclinically driven cyclones.

The analysis described above used the Plugin ZYKPAK for the cyclone tracks. Additionally, storage and computing resources on Levante were used.

Due to a change in project members, with Dr. Ting-Chen Chen being replaced by Svenja Christ as a new PhD student, the planned ICON-CLM simulations have been postponed to next year. As a result, the requested resources for 2024 have not been fully utilized, as the simulations have not yet been conducted.

3.2 Project related publications:

Quinting, J.F., Grams, C.M., 2022. Eulerian Identification of ascending AirStreams (ELIAS 2.0) in numerical weather prediction and climate models – Part 1: Development of deep learning model. Geoscientific Model Development 15, 715–730. https://doi.org/10.5194/gmd-15-715-2022

Quinting, J.F., Grams, C.M., Oertel, A., Pickl, M., 2022. EuLerian Identification of ascending AirStreams (ELIAS 2.0) in numerical weather prediction and climate models – Part 2: Model application to different datasets. Geoscientific Model Development 15, 731–744. https://doi.org/10.5194/gmd-15-731-2022

4. Module B – B1.3 Patteta

Subproject: B1.3: Process-based attribution of extreme temperatures to anthropogenic drivers
Subproject leader: Sebastian Sippel (Uni Leipzig)

4.1 Usage report May 2025 – October 2025

We have started to use resources from early 2024 onwards, focusing on mainly two topics:

1. **The impact of aerosol forcing on the statistical attribution of heatwaves (PATTETA WP1)**

After downloading the large ensemble single forcing model simulations from CESM2 to DKRZ, we have also begun using other single forcing model simulations from CMIP6. In single forcing simulations, only one forcing (e.g., anthropogenic aerosols or greenhouse gases) is changed, while all others remain unchanged or all but one are changed (e.g. all but anthropogenic aerosols). We used these simulations to evaluate the robustness of statistical attribution approaches. A key result is shown in Figure 6; a peer-reviewed scientific paper is published (Kraulich et al., 2025).

We showed that not explicitly accounting for regional anthropogenic aerosols leads to substantial biases in the statistical attribution of heat extremes. By using single forcing large-ensemble model simulations we confirmed that the bias is indeed caused by anthropogenic aerosols and we proposed a change in the statistical attribution method that includes regional aerosols. Building on the published work, we further disentangle the effects of aerosols and greenhouse gases. We now examine how the different forcings contribute to the increasing frequency of record-breaking heat extremes in Europe and beyond.

2. **Preparation and climate simulations with the Community Earth System Model Version 2 (CESM2) on Levante (PATTETA WP2 & WP3)**

We ported and installed the climate model CESM2 on Levante for WP2 and WP3. After initial testing, since summer 2024, we have conducted larger simulations. We describe the state of the simulations in more detail below:

- Small CESM2 ensemble for boosting and/or importance sampling

We simulated a 42-member CESM2 (fully coupled) ensemble for the period 2021-2031 representing current climatic conditions. The initial conditions for the ensemble are taken from another similar ensemble simulated at ETH-Zürich. Additionally, we simulated a 450-year piControl simulation with CESM2. This current climate ensemble and the piControl run will be used for dedicated ensemble boosting and importance sampling experiments allowing for a comparison between current and pre-industrial climate. Note that, although similar ensembles already exist, we had to re-simulate these ensembles to allow bit-by-bit reproducibility on levante which is required for ensemble boosting.

- Generation of worst-case heat wave simulations in CESM2

We created simulations of hot summers over Europe using a rare event algorithm (Ragone and Bouchet, 2021, *Geophysical Research Letters*, doi:10.1029/2020GL091197). The method consists of simulating a large ensemble by regularly stopping the simulation (every 5 days) and systematically discontinuing some simulations and cloning others by adding a tiny perturbation. This evaluation step is stochastic but with a weighting based on a variable of interest (in our case warm conditions in Europe) such that simulations that are cold in Europe are more likely to be discontinued and simulations that are warm are likely to be cloned. As initial conditions we use the years 2024, 2025 and 2026 from a 42-member ensemble for the scenario SSP3-70 (simulated in the previous phase/period) resulting in 126 independent initial conditions for the current climate. Additionally, we take 126 years from a piControl run as starting conditions for a pre-industrial climate. Since the algorithm has a stochastic element we simulated 5 ensembles for current and 5 ensembles for pre-industrial climate. The obtained ensembles contain many one-in-a-hundred-year summers allowing to statistically analyze differences in the characteristics of one-in-a-hundred-year summers. First results indicate, that changes in extreme summers are more pronounced than changes in average summers. For instance, the difference in the number of hot days between current and pre-industrial climate is considerably larger when only analyzing 1-in-100 years summers. A paper draft that analyzes these simulations is in preparation (Pfleiderer et al., in prep.). The simulations are shared within the ClimXtreme projects Freva data browser: https://www.xces.dkrz.de/databrowser/?project=extremes&start=0

- **Nudged circulation simulations with CESM2**

We implemented and tested a nudged circulation simulation setup in CESM2. In this framework, CESM2 is constrained with observed ERA5 horizontal winds and run under different climate forcing levels. This setup allows us to reproduce the internal climate variability of hydroclimatic variables and observed climate trends, providing a versatile tool for attribution-related studies by separating uncertainties originating from circulation and thermodynamic processes. The first application of this framework focuses on the circulation-driven component of the current European drying trend and is currently under revision in *Nature Geoscience* (Dunkl, Bastos, Sippel, n.d.). Those simulations were also used as a benchmark case of statistical and machine learning methods to separate dynamical from thermodynamic temperature trends (Pfleiderer et al., 2025). Building on this foundation, we will extend the setup for a series of single-forcing nudged circulation simulations within ClimXtreme II, aimed at disentangling the respective roles of greenhouse gases and aerosols in driving temperature and hydroclimate extremes. These forthcoming experiments will directly contribute to the objectives of PATTETA and ClimXtreme II, advancing our understanding of the physical drivers behind observed and projected climate extremes.

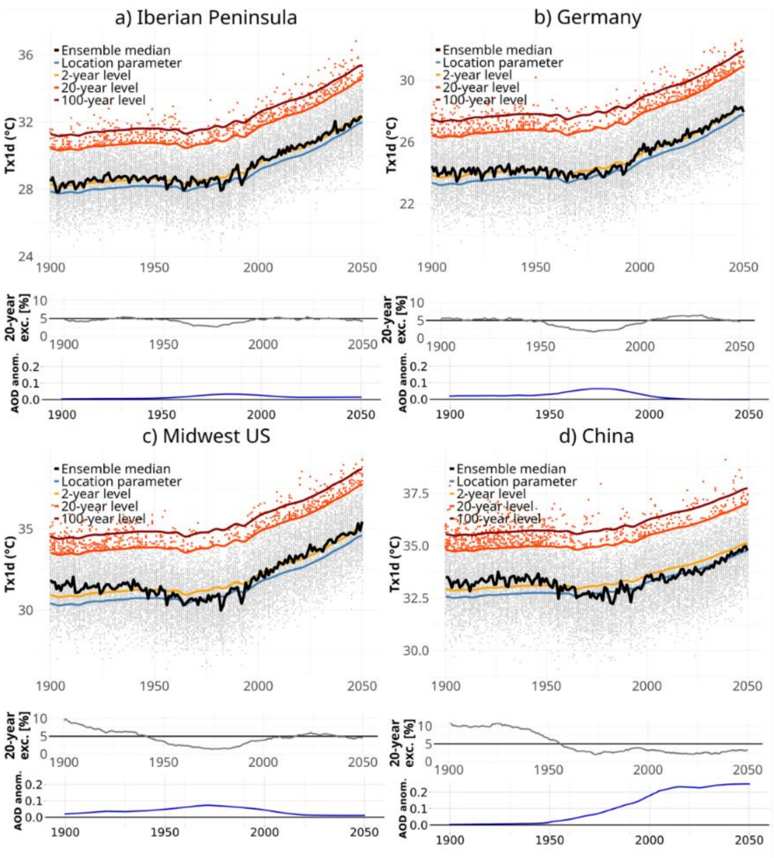

Figure 6: Analysis of CESM2-LE Tx1d using the "standard statistical attribution method" for (a) Iberian Peninsula, (b) Germany, (c) Midwest US, and (d) China. Top: CESM2-LE Tx1d with location parameter and return period levels. Grey dots show the individual years of the ensemble simulations, and the black line represents the ensemble median. Tx1d above the 20-year level are indicated with red. Middle: 20-year running mean of the probability of exceedances of the 20-year return period level. Bottom: Trend of 20-year smoothed mean AOD in JJA as anomaly to 1850−1900 average. Reference: Kraulich, F., Pfleiderer, P., and Sippel, S.: The impact of aerosol forcing on the statistical attribution of heatwaves, Weather and Climate Extremes, 50, 100803, https://doi.org/10.1016/j.wace.2025.100803, 2025.

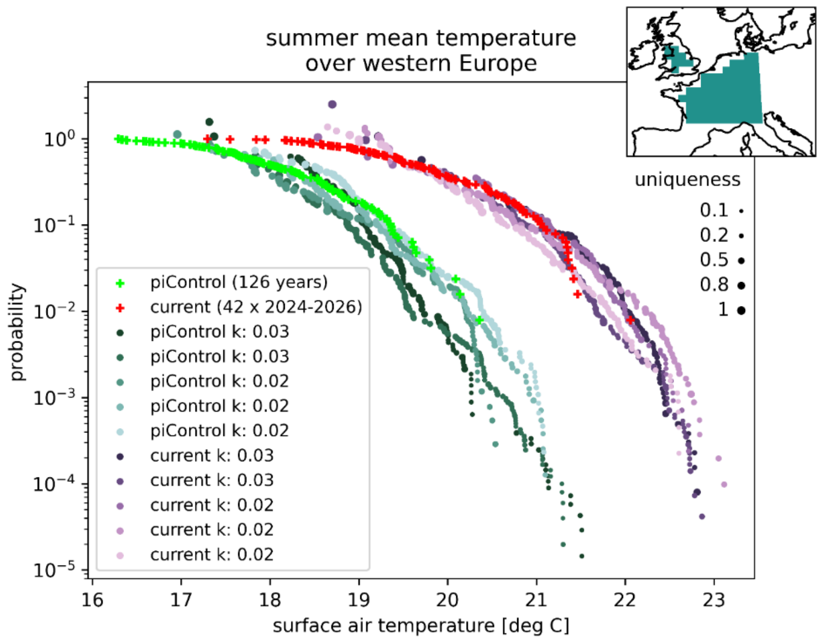

Figure 7: European summer temperatures (JJA) by probability of occurrence in importance sampling simulations. Each dot represents one simulated summer. The green and red crosses are the initial simulations without the rare event algorithm. The other dots are simulation resulting from the rare event algorithm. Each color represents one ensemble. Greenish colors for pre-industrial climate and red colors for current climate. The size of the dots represents the uniqueness of the simulation reflecting that some simulations share parts of the summer with another simulation (smaller dot in this case). The region over which surface air temperatures are averaged is shown in the top right.

4.2 Project related publications:

Dunkl, I., Bastos, A., and Sippel, S.: Recent European drying driven by circulation and dynamic-thermodynamic interactions, Nature Geoscience (Under Review)

Kraulich, F., Pfleiderer, P., and Sippel, S.: The impact of aerosol forcing on the statistical attribution of heatwaves, Weather and Climate Extremes, 50, 100803, https://doi.org/10.1016/j.wace.2025.100803, 2025.

Pfleiderer, P., Merrifield, A., Dunkl, I., Durand, H., Cariou, E., Cattiaux, J., and Sippel, S.: The contribution of circulation changes to summer temperature trends in the northern hemisphere mid-latitudes: A multi-method quantification, EGUsphere, 1–28, https://doi.org/10.5194/egusphere-2025-2397, 2025.

5. Module B – B2.4 XPreCCC

Subproject: B2.4: Characterizing eXtreme Precipitation events under Climate Change Conditions
Subproject leader: Henning Rust (FU Berlin)

5.1 Usage report May 2025 – October 2025

The work performed during the reporting period is in line with that outlined in the main proposal for the year 2025 (i.e. excluding the additional resources application for the second half of 2025, in which no additional model experiments were proposed). Specifically, and, as in previous reporting periods, event-based ensemble sensitivity simulations have been performed at convection-permitting resolution over central Europe. The focus event chosen was a 10-day period of unusually high convective activity over Germany during summer 2016 (Piper et al., 2016). Pseudo-global warming experiments (e.g. Schär et al., 1996) had been performed for this event previously in the project (Meredith et al., 2023). The associated ensemble was expanded to both increase the number of members and assess the impact of the warming profile on the climate-change signal. Specifically, warming signals based on (i) a EURO-CORDEX ensemble mean and (ii) a neutral warming profile were imposed on the simulation period (Figure 8).

On completion of these simulations, the tracking algorithm described in Meredith et al. (2023) was applied to the ensemble's precipitation output, a time-consuming process running on a single processor. The analysis of the algorithm's output is ongoing.

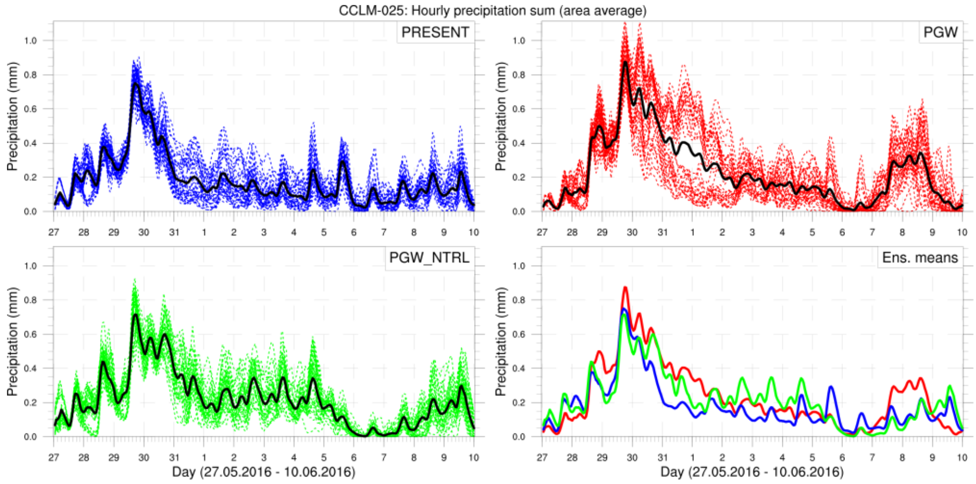

Figure 8: Hourly time series of area mean precipitation for the present climate (top left), pseudo global warming climates with heterogeneous (top right) and homogeneous (bottom left) warming profiles, as well as the respective ensemble means (bottom right)

The archive storage space granted to the sub-project for 2025 proved to be insufficient to meet the needs of the experiments. A revised estimate has thus been included in the latest proposal.

The work performed since May 2025 has been in accordance with that envisaged in the original proposal.

5.2 Project related publications:

Meredith, E. P., Ulbrich, U., and Rust, H. W. (2023). Cell tracking of convective rainfall: sensitivity of climate-change signal to tracking algorithm and cell definition (Cell-TAO v1.0), Geosci. Model Dev., 16, 851–867, https://doi.org/10.5194/gmd-16-851-2023.

6. Module C – C3 CROP4EUROPE

Subproject: C3: Impacts of compound weather extremes on crops in Germany: present and future
Subproject leader: Elena Xoplaki (Uni Giessen)

6.1 Usage report May 2025 – October 2025

During the reporting period we further refined and tested the AI surrogate model for the crop growth model ECroPS. The crop growth period is now fully emulated by the surrogate model extending beyond growth stages Development Stage (DVS) DVS1 to DVS2, from sowing date to end of each year. The AI surrogate was also trained anew using all available cells instead of just cells that have a minimum set yield, thus now rendering the surrogate model fully functional.

To evaluate its performance anew, the model's predictions were compared against an unseen test dataset and validated using ground-truth data forced with ERA5 reanalysis, using the Fréchet distance among other metrics. The Fréchet distance distribution is presented in Figure 9, alongside a randomly selected illustration of grid cell-level Total Weight of Storage Organs (TWSO) dynamics shown in Figure 10.

The surrogate's outputs are used to compute categorical Areas of Concern (AoC) for European agriculture—defined as regions experiencing ≥5% yield loss relative to a reference mean.

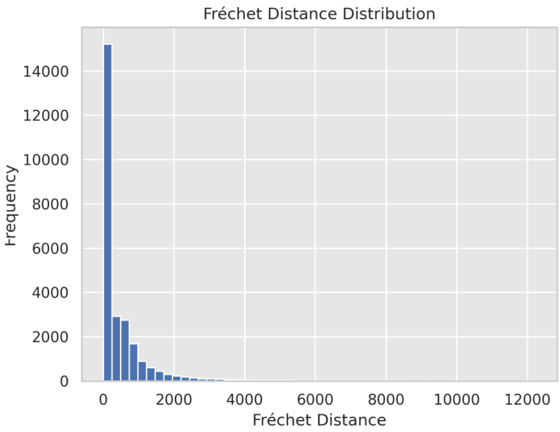

Figure 9: Fréchet distance distribution histogram.

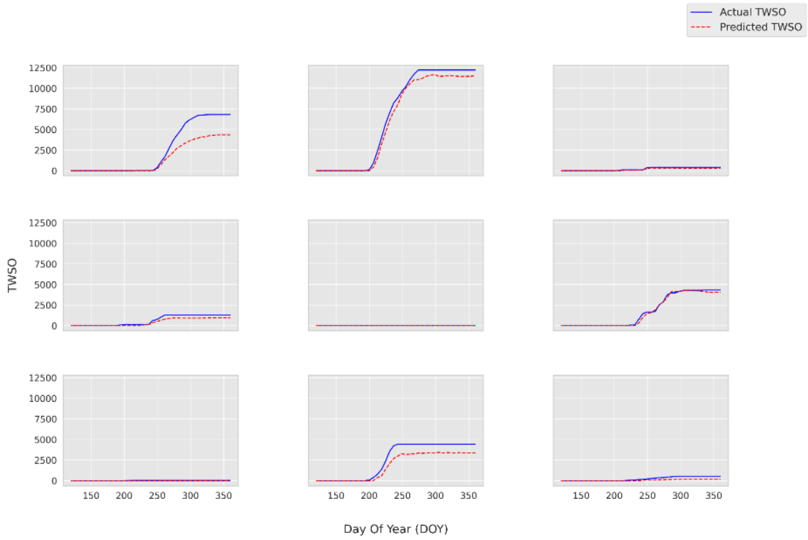

Figure 10: Random samples with overlaid crop growth timeline in terms of actual and predicted TWSO.

During the reported time, for the compound extremes detection, drivers' assessment and impact pipelines we generated yields using EOBS and conducted index calculations for extreme events also using the EOBS dataset aligning with the bias adjustment of the EUR-11 projections, such as the Heat Magnitude Day (HMD) for years 1985 to 2024. The ongoing analyses include EUR-11 projections that are going to be utilized for the story maps and serve as the basis for the engagement with stakeholders.

7. Module C – C5 FLOOD

Subproject: C5: Linking extreme, large-scale river floods and their impacts in Central Europe to climate and weather mechanisms

Subproject leader: Viet Dung Nguyen, Sergiy Vorogushyn, Bruno Merz, Heidi Kreibich

7.1 Usage report May 2025 – October 2025

During the 2025b allocation period, we made intensive use of the Levante supercomputing infrastructure at the Deutsches Klimarechenzentrum (DKRZ) as part of the ClimXtreme II – FLOOD (C5) subproject. The work focused on the impact attribution of the 2021 Ahr flood, aiming to quantify how climate change influences flood generation and impacts across multiple system levels — from precipitation and runoff to inundation and loss.

The computational workflow consisted of a **fully coupled Regional Flood Model (RFM) chain**, integrating hydrological and hydraulic simulations with impact metrics. We focused on several diagnostic indicators: (1) 1-day and 2-day regional precipitation maxima, (2) event peak discharge at the Altenahr gauge, (3) hydraulic descriptors such as maximum inundation extent and mean inundation depth, and (4) damage-related impact indicators.

Hydrological input data were derived from long-term stochastic simulations generated in earlier project phases. These simulations consist of hourly time series for **400 realizations x 30 years, representing seven scenarios** — one historical baseline and six GCM-based experiments corresponding to the counterfactual (pre-industrial or historical natural) climate conditions. Using these data, we extracted **3,402 discrete flood events** at Altenahr, each lasting up to seven days, by identifying discharge peaks above a prescribed threshold. This extraction and organization phase was fully CPU-bound and executed efficiently on Levante's compute nodes.

The extracted flood hydrographs were then used as inflow boundary conditions for the inundation model configured for the downstream reach of Altenahr, based on the RIM2D two-dimensional hydrodynamic framework. RIM2D solves a simplified form of the shallow-water equations on a raster grid, enabling computationally efficient simulations at high spatial resolution. In this study, **a 5 m grid** spacing was applied, corresponding to approximately **six million computational cells** covering the lower Ahr valley downstream of Altenahr.

To achieve the required throughput, all RIM2D simulations were executed on the GPU partition of the Levante system, primarily utilizing the NVIDIA A100-80 GPU architecture. **Each job requested four GPUs, one CPU core, and 20 GB of memory**. A single job corresponded to one flood event, with typical wall-clock times ranging from 10 to 20 minutes, depending on hydrograph duration. The model, implemented in Fortran with CUDA extensions and compiled using the NVIDIA HPC Toolkit (nvfortran), exhibits excellent GPU scalability and high computational efficiency. All simulations were submitted and managed as SLURM array jobs, enabling the concurrent execution of several hundred events and ensuring optimal utilization of Levante's GPU resources.

The overall simulation campaign ran very reliably. The combination of Levante's fast I/O subsystem and GPU-accelerated nodes proved essential for large-ensemble hydraulic modeling. Efficient queue management, job stability, and system responsiveness allowed sustained high utilization without major interruptions.

Figure 11 illustrates **two representative examples** from the simulation campaign. Both events fall within the category of hydrologically extreme floods at the Altenahr gauge, yet they differ strongly in magnitude and temporal dynamics. The upper panels correspond to a high-intensity but short-duration event with a peak discharge of about 300 m^3/s, a total volume of 40.9 Mm^3, and a duration of roughly three days. The lower panels depict an exceptionally severe flood, reaching a simulated peak discharge of 1,217 m^3/s and a total volume of 110 Mm^3 over a period exceeding six days. This event is substantially more intense than the observed Ahr flood of July 2021. Together, these examples highlight the model's ability to represent a wide range of extreme flood magnitudes and to reproduce highly nonlinear floodplain responses under varying hydrological conditions.

These simulations demonstrate the capability of the developed GPU-accelerated workflow to reproduce hydrological and hydraulic extremes at high spatial detail. The DKRZ infrastructure was instrumental in enabling the large-scale, high-throughput modeling required for robust probabilistic flood impact attribution within the ClimXtreme II project.

The simulation campaign ran smoothly and efficiently, thanks to the **excellent performance of the Levante GPU system**. Without the fast hardware and reliable support from DKRZ, this work could hardly have been completed in time. In the next step, we will carefully analyze the simulation outputs, validate the results, and use them in the attribution study to quantify climate-change impacts on flood intensity and extent. **More simulations are still needed** — as planned, we aim to reach about 10,000 events in total, and some reruns will be required to improve coverage and consistency.

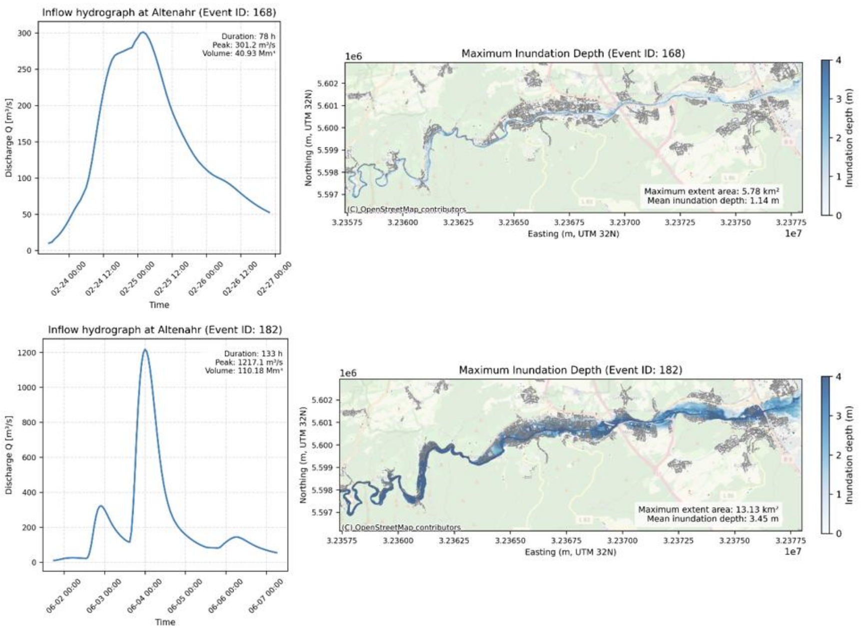

Figure 11. Simulated inflow hydrographs (left) and maximum inundation depths (right) at Altenahr for two extreme flood events illustratively selected from more than 3,000 extracted events.

8. Module D – CoSoDaX

Subproject: bb1159 (D1/D2): Coordination of software and data management for ClimXtreme
Subproject leader: Etor Lucio-Eceiza, Torben Kunz, Deborah Niermann

8.1 Usage report May 2025 – October 2025

Module D is a supporting module of the ClimXtreme research project and is responsible for the coordination of software and data management (CoSoDaX). In addition to the general coordination activities, this includes the following main contributions: (a) the development and operation of a central evaluation system for climate extremes (XCES [1]), (b) the provision and analysis of basic data sets for the evaluation of climate extremes, (c) the support of software developments for the investigation of extreme events and the maintenance of existing software.

XCES is based on Freva (Kadow et al., 2021), a scientific software framework for high performance computing, equipped with a standardized model database, a programming interface and a history of evaluations, maintained and updated by the Climate Informatics and Technologies (CLINT [2]) group at DKRZ.

One of the primary goals of Module D is to build up a reasonable database for the joint project, accessible through XCES. Based on the data from the former MiKlip project [3], this data collection has been progressively expanded during the first phase of ClimXtreme by the following relevant datasets: RADKLIM, EOBS, HYRAS-DE, ERA5. Currently more than 10 million files totaling more than 5 PB of data can be accessed through XCES. Although the vast majority of the data is linked from the /pool/data, a significant amount of it is hosted under the joint project bm1159 (around 285 TB). An overview of the data types integrated in the system and hosted with resources of bm1159 (subproject of bb1152) is given in Figure 12.

XCES grants a flexible incorporation of scientific analysis tools (plugins). These analysis tools are being developed by Modules A-C with the assistance of Module D, or by Module D itself to fulfill the needs of the project and be used by any member of the Consortium. There are currently 29 plugins available to all members via the XCES, with additional plugins being at different developmental stages not yet included in the XCES. During the reporting period, 2 plugins, previously at developmental stage, could be made available to the XCES with the support of Module D, namely, the plugin CROPS from project C3 (which analyses extreme and compound events on crops) and the plugin Predict_Building_Damage from project COO (which computes the loss ratio threshold exceedance probability for a single winter storm event over the domain of Germany).

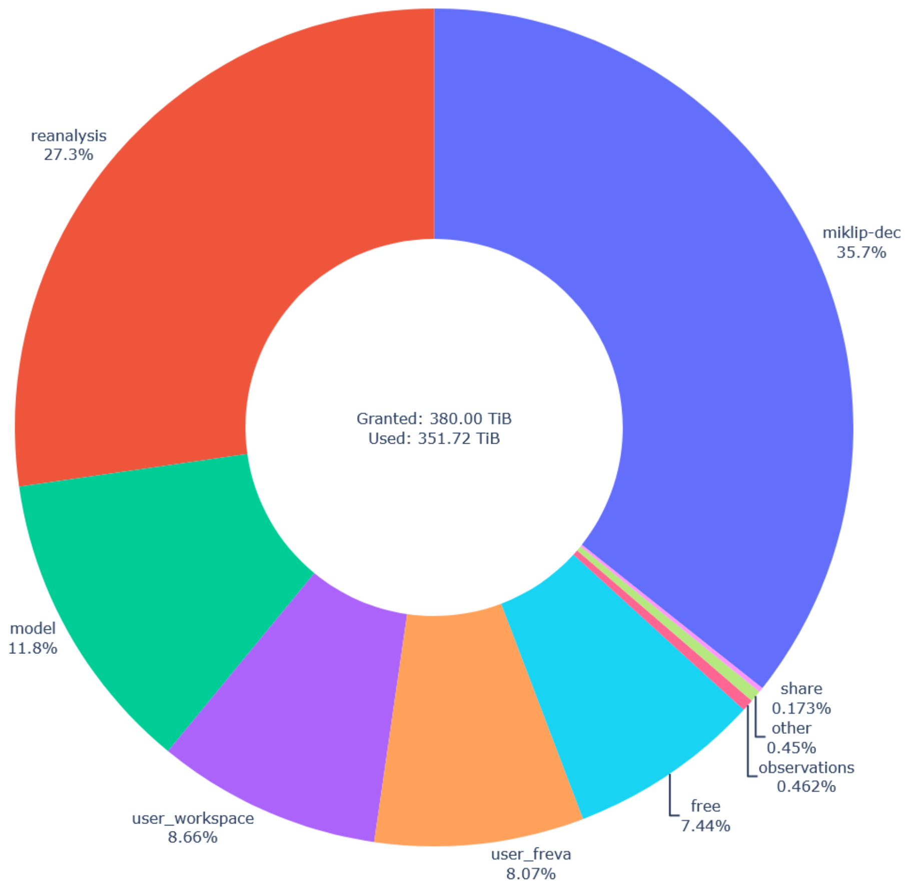

Figure 12: Storage demand (TiB) under /work/bm1159/XCES/ on 21.10.2025, hosted in the ClimXtreme project bm1159, and percentage of data according to their type.

The abovementioned 29 plugins are hosted and run through XCES and are available to the entire ClimXtreme community. During the reporting period several thousand plugin calls have been made so the amount of storage allocated to outputs has grown steadily. XCES users currently use close to 64 TiB including plugin outputs, data indexed back to XCES, and their own workspace. Various plugins developed within as well as data accessible through XCES have been used for several event studies and publications within the project.

One particular advantage of the XCES is its programming interface, specifically its python API, which makes it easy to include plugin calls into python scripts, performing scientific analyses based on a number of various plugins. During the reporting period, Module D specifically supported Module C in the development of workflows (realized as python jupyter notebooks) designed for a quick analysis of recent extreme weather events of various types. This task is part of the ClimXtreme Post event Assessment Group (PostAG) to enable the Consortium to quickly react and publish statements (like those listed in section 9.2) on extreme weather events occurring during the project runtime. Figure 13 illustrates such a workflow for the event type 'winter storm', combining multiple XCES plugins in one analysis. Apart from collaborations within ClimXtreme, like PostAG, bm1159 resources were also used for collaborations with further parties. A study from project CARLOFF from University of Potsdam with participation of KIT and DWD, combined a wide small-scale hydrological model with an ensemble of six convection permitting models. The small spatial and temporal resolution of this ensemble allows for a simulation of (flash) floods in small scale catchments for the whole of Germany under the RCP8.5 scenario. The results will help to understand changes in flood hazard due to changes in rainfall extremes. To our knowledge this is the first Germany wide assessment of this kind. Manuscript submission is planned beginning of November.

The total CPU usage between data and plugin runs until the end of October 2025 adds to almost 6,700 node hours, that is, around 99.5% of the granted resources for the complete 2025 period. This demonstrates, that the granted resources are, at best, marginally sufficient, given the needs of the project.

An adjacent line of research of CLINT is focused on the application of AI/ML methods (Kadow et al., 2020) to tackle a variety of climate science related topics, with a direct usability through XCES (i.e., data and plugins) in mind. The research group has been further developing these methodologies under HLRE 4's GPU cores. Examples of recent lines of research are the following: infilling of observations for data assimilation for the improvement of numerical climate prediction systems in relation to extremes; prediction of extremes in temperature measurements and digital twins; and the creation of a classifier tool for climate model seasonal predictions of extremes (the later has also extensively used decadal prediction plugins developed within MiKlip that were re-adapted during the last period of Phase1, and that will be needed in the upcoming Coming Decade Freva sister project). Around 85% of the GPU resources granted for the complete 2025 period have been used until the end of October 2025.

8.2 Project related publications:

Grieger, J., Kunz, T., Buschow, S., Daniell, J., Lucio Eceiza, E. E., Fauer, F. S., ... & Vorogushyn, S. (2024). Dauerniederschläge und Weihnachtshochwasser im Winter 2023/24. http://dx.doi.org/10.17169/refubium-43523 (Technical report)

Friederichs, P., Grieger, J., Kunz, T., Ulbrich, U., Bürger, G., Buschow, S., ... & Vorogushyn, S. (2024). Ergiebige Dauerniederschläge und Hochwasser in Süddeutschland im Mai und Juni 2024. http://dx.doi.org/10.17169/refubium-44009 (Technical report)

9. References

Fink, A.H., Pohle, S., Pinto, J.G., Knippertz, P., 2012. Diagnosing the influence of diabatic processes on the explosive deepening of extratropical cyclones. Geophysical Research Letters 39. https://doi.org/10.1029/2012GL051025

Kadow, C., Hall, D. M., Ulbrich, U., 2020: Artificial intelligence reconstructs missing climate information. *Nature Geoscience*, 1-6

Kadow, C., et al. "Introduction to Freva–A Free Evaluation System Framework for Earth System Modeling." *Journal of Open Research Software* 9.1 (2021).

Piper, D., et al. (2016): Exceptional sequence of severe thunderstorms and related flash floods in May and June 2016 in Germany – Part 1: Meteorological background, Nat. Hazards Earth Syst. Sci., 16, 2835–2850, https://doi.org/10.5194/nhess-16-2835-2016.

Röthlisberger, M., & Papritz, L. (2023). A global quantification of the physical processes leading to near-surface cold extremes. *Geophysical Research Letters*, *50*(5), e2022GL101670.

Schär, C., et al. (1996). Surrogate climate-change scenarios for regional climate models, Geophys. Res. Lett., 23, 669–672, https://doi.org/10.1029/96GL00265.

[1] https://www.xces.dkrz.de/

[2] https://www.dkrz.de/de/kommunikation/aktuelles/ki-gruppe_dkrz

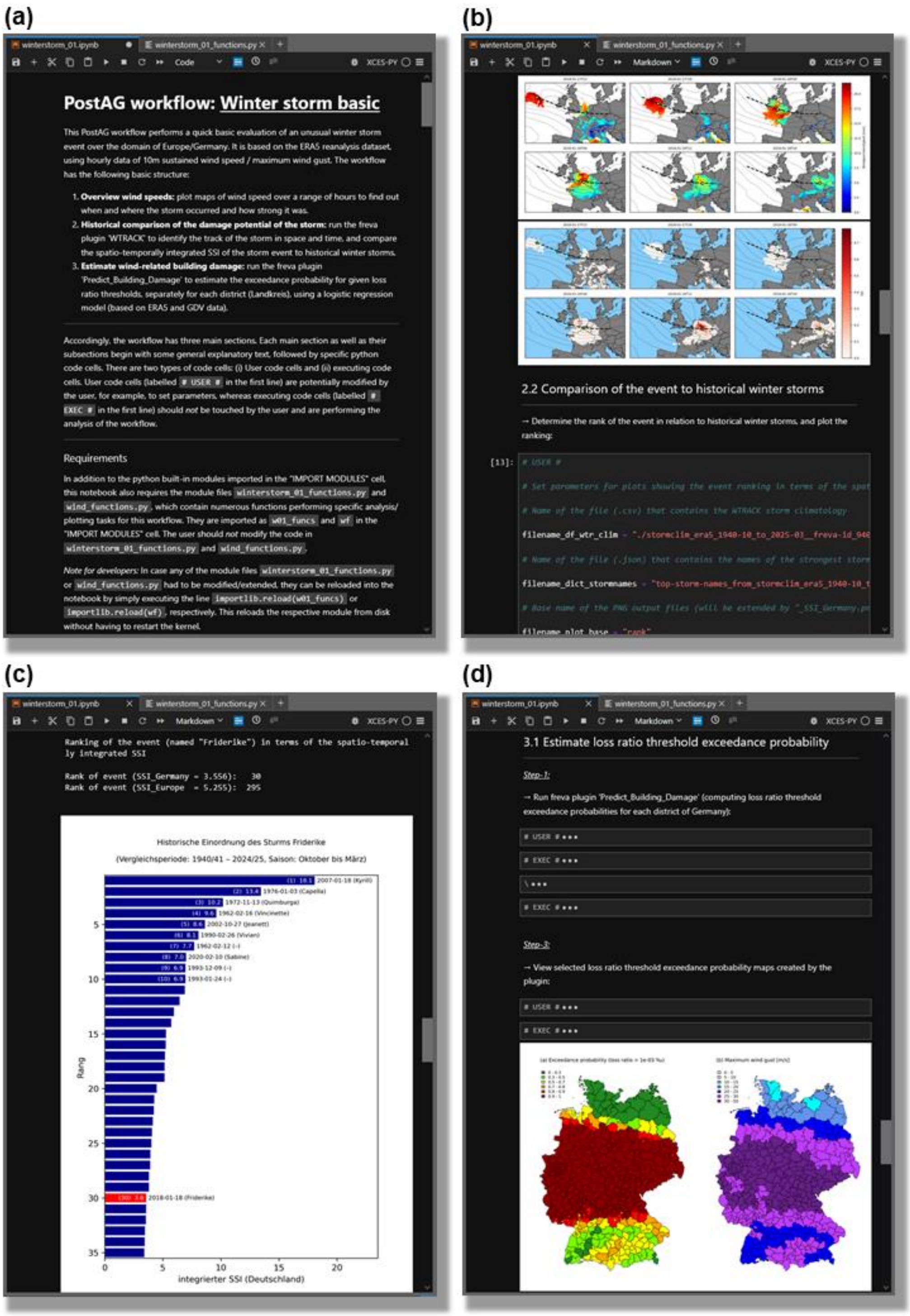

Figure 13: Snapshots from an example workflow (a-d, python jupyter notebook) for the ClimXtreme Post event Assessment Group (PostAG) for the event type 'winter storm', employing and building upon multiple XCES plugins, namely, (b, c) WTRACK and (d) Predict_Building_Damage.