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: 2026

Table 1: Used resources at DKRZ (by end of October 2026) in project bb1152 (and subproject bm1159).

Resource bb1152	Granted	Utilization	Remaining
Levante CPU nodes (Node hours)	30294	20404	9890
Levante GPU nodes (Node hours)	2231	1468	763
Levante Storage (TiB)	377	320	57
Archive project (TiB)	488 (thereof 315 purchased)	-69	557 (thereof 315 purchased)
Archive long term (TiB)	7	279	-272
Resource bm1159	Granted	Utilization	Remaining
Levante CPU nodes (Node hours)	6766	5453	1313
Levante GPU nodes (Node hours)	2328	1869	459
Levante Storage (TiB)	345	325	20
Archive project (TiB)	135	0	135
Archive long term (TiB)	0	0	0

Scientific activities conducted during the report time

For those projects which were granted *additional* resources for the second half of 2026 and, thus, reported the last time in April 2026, the current reporting period is 05/2026 – 10/2026, whereas for those ones which did not request *additional* resources and, thus, reported the last time in 10/2025, the current reporting period is 11/2025 – 10/2026.

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 November 2025 – October 2026

The projects contributed with analysis, plots and writing to several ongoing publications, which have already been submitted (Voit et al., 2026; Hense et al., 2026, Sieck et al., 2026, Braun et al., 2026., Medvedova et al., 2026) and are now under revision. Furthermore, there are several published works with contributions from the project members, namely Beyer et al. (2026) and Pinto et al. (2026).

A specific topic in 2026 was the consistency of GCM and RCM results from CMIP6 downscaling (Cusinato et al., 2026). The paper found, that global and downscaled regional climate simulations show similar bias patterns, if the GCM forcing data provide physically consistent forcing for the downscaling. If the GCM data are physically imbalanced, the regional adjust them. An example can be seen in Fig 1.: whereas for EC-Earth3-Veg (first row) and MPI-ESM-HR (second row) GCM and downscaling simulations provide in general similar bias patterns, MIROC6 shows a strong hot bias for summer near-surface temperature. The RCMs are able to reduce this bias. Over land the adjustment occurs via the surface fluxes between the interactive representation of the soil. Over the ocean the RCMs use the sea surface temperatures from the GCMs directly, since no ocean model is coupled. There the evaporation increases strongly due to the high temperatures, which creates a strong vertical moisture flux, which causes a strong local to regional precipitation surplus.

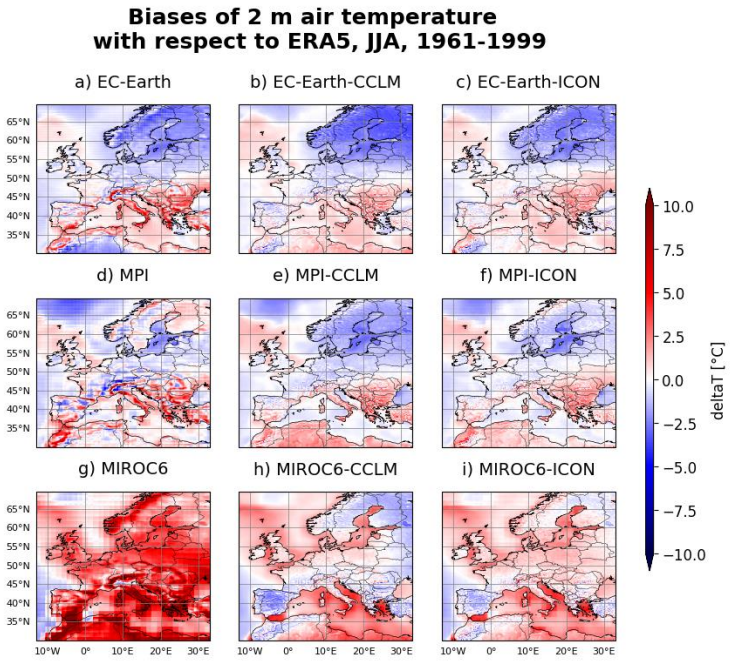


Figure 1: Biases of 2 m air temperature with respect to ERA5 over the European domain in JJA for 3 different CMIP6 GCMs (left column) and downscaling simulations with COSMO-CLM (middle column) and ICON-CLM (right column). From: Cusinato et al., 2026.

1.2 Project related publications:

Beier, C., Ziegler, K., Paeth, H., Pinto, J.G., Sieck, K., Buntemeyer, L., Geyer, B., Xoplaki, E., Espitia, E., Braun, C., Ehmele, F., Feldmann, H., Kadow, C., Trachte, K., 2026: NUKLEUS-A First Convection-Permitting Multimodel Ensemble for Germany: Assessment of Future Changes in Temperature and Precipitation Extremes. J. Climate, 39, 6145-6168, https://doi.org/10.1175/JCLI-D-25-0613.1.

Braun, C., Ehmele, F., Beier, C., Espitia-Sarmiento, E. F., Feldmann, H., Frisius, T., Geyer, B., Hundhausen, M., Keuler, K., Luterbacher, J., Sieck, K., Trachte, K., Xoplaki, E., and Pinto, J. G.: NUKLEUS – A first kilometer-scale convection-permitting multi-model climate ensemble for Germany: Characteristics of the historical simulations 1961–1990, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2517, 2026.

Cusinato, E., Feldmann, H., Geyer, B. Ludwig, P., Trachte, K., Pinto, J.G., 2025: From Global to Regional Climate Models: Consistency Assessment of the Hydrological Cycle. Climate Dynamics, under revision

Hense, A., Kottmeier, C., Friederichs, P., Buschow, S., Szemkus, S., Ulbrich, U., Grieger, J., Pinto, J. G., Feldmann, H., Kaspar, F., Niermann, D., Lorenz, R., Ruff, F., and Lucio Eceiza, E. E.: Past and future European atmospheric extreme events under climate change – the ClimXtreme program's structure and results, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2697, 2026.

Medvedova, A., Ban, N., Kohlhauser, I., Maraun, D., Rotach, M.W., Ahrens, B., Bastin, S., Brienen, S., Feldmann, H., Goergen, K., Hodnebrog, O., Katragkou, E., Kendon, E., Milovac, J., Raffa, M., Sieck, K., Sobolowski, S., Tölle, M.H., Truhetz, H., Warrach-Sagi, K. (2026): Temperature-dependent Hourly Precipitation Biases in Convection-parameterizing Regional Climate Models: Insights from a Kilometer-scale Ensemble. GRL, under revision.

Pinto, J. G., M. Hundhausen, A. Weber, et al. 2026. “User-Relevant Climate Indices and Associated Uncertainties from Transient Convection-Permitting Climate Model Projections.” International Journal of Climatology 46, no. 6: e70304. https://doi.org/10.1002/joc.70304.

Sieck, K., Pinto, J. G., Geyer, B., Keuler, K., Beier, C., Braun, C., Ehmele, F., Feldmann, H., Frisius, T., Heinrich, P., Hundhausen, M., Petrik, R., and Trachte, K.: NUKLEUS – A First Kilometre Scale Multi-Model Climate Ensemble for Germany: Evaluation, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-1024, 2026.

Voit, P., Hundhausen, M., Seregina, L., Feldmann, H., Ahrens, B., and Heistermann, M.: Southern Germany's 100-year flash flood discharge expected to increase by 30 % under an RCP8.5 climate, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-1229, 2026.

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 November 2025 – October 2026

As mentioned in the previous report, in WP1 of module 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, we finished the revision and were able to publish an article on differences in heat-generating processes between ridge- and Omega-type heatwaves in the current climate, based on an extensive Lagrangian temperature decomposition applied to a large number of trajectories (Lemburg et al., 2026a).

Thereafter we shifted our focus on future projections for a 3K warmer world and investigated the projected changes of both atmospheric blockings and subtropical ridges for Europe and their relationship to heat extremes. For this analysis, we used climate projections from two single model initial-condition large ensembles (SMILEs), namely MPI-GE and SMHI-LENS.

Over large regions of Central Europe, both SMILEs project a significantly increased fraction of heatwave days linked to subtropical ridges, such that they become the dominant driver of heatwaves over most of Central Europe (Fig. 2). At the same time, the fraction of heatwaves linked to atmospheric blocking decreases. This is consistent with an overall decrease in summer-time blocking of about 10-20% which is compensated by an increase in the occurrence of ridges by nearly 15% in the Central European region. Based on these findings, we suggest that the northward extension of the subtropical high-pressure belt under a warming climate makes atmospheric blocking less of a necessary phenomenon to induce heatwaves in mid-latitude regions.

We have recently submitted our work and are currently awaiting reviews (Lemburg et al., 2026b, submitted).

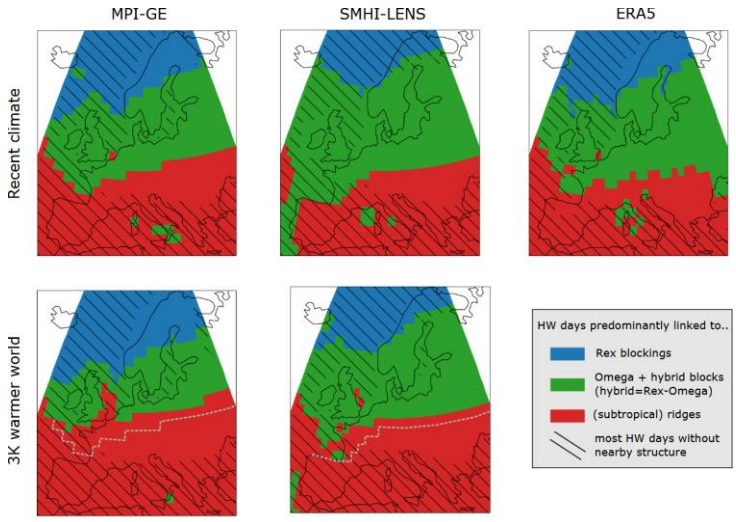


Figure 2: Overview of the dominant anomalous large-scale circulation feature during HW days in Europe, based on ERA5 and the respective averages across the MPI-GE and SMHI-LENS model ensembles. The top row shows the situation for the recent climate (+0.75K warming level compared to pre-industrial, 1950-2023 for ERA5) for MPI-GE (a), SMHI-LENS (b) and ERA5 (c), while the bottom row shows results for projections of a 3K warmer world in MPI-GE (d) and SMHI-LENS (e). For better visual comparison, the bottom plots feature a silver dashed line that represents the latitude at which HW days transitioned from ridge- to atmospheric blocking-dominated in the recent climate.

Within Work Package 2 (WP2: Attribution of changes of heat wave projections, Hereon) of ClimXtreme Module A5 (DesAttHeat), the spectrally nudged storyline approach (van Garderen et al., 2021) is applied to perform a physical

attribution of past extreme events. This is achieved by constructing multiple storylines of the same event under different climate conditions: Counterfactual (pre-industrial), Factual (present-day), and warmer climates (+X K relative to pre-industrial levels). The storylines differ only in sea surface temperatures and greenhouse gas concentrations, as these variables are strongly influenced by anthropogenic forcing. Spectral nudging is used to constrain large-scale atmospheric circulation towards reanalysis data, ensuring that the simulated events remain dynamically consistent with observed historical conditions while allowing thermodynamic differences across scenarios. Previous work within the group has employed global storylines using ECHAM6 (T255 resolution), for example in the analysis of the 2022 European heatwave (Feser et al., 2024). We further combined conditional attributional methodologies to introduce a physical-statistical attribution framework to account for changes in event intensification and the associated probability of occurrence (León-FonFay, 2026a). We also explored the role of heat in promoting fire-weather conditions across Europe, focusing on the 2025 Mediterranean fire-weather season (van Garderen, under review). Furthermore, the storyline approach was extended from the attribution of individual events to the analysis of a decade of extreme events in South America (León-FonFay, 2026b). This work ultimately led to a discussion on the opportunities and challenges of extending attribution concepts from weather to climate (León-FonFay, under review).

In the second phase of the project, these global storylines are dynamically downscaled to the EURO-CORDEX domain using COSMO-CLM. To maintain consistency with the global ECHAM storylines, regional COSMO-CLM storylines were simulated for the same warming levels (Counterfactual, Factual, +2 K, +3 K, +4 K), covering the EURO-CORDEX region at 0.11° resolution for the period 2015 to 2025 (Fig. 3). Each storyline includes three ensemble members initialized with slightly perturbed initial conditions, forming small ensembles that allow assessment of the robustness of attribution results. The dataset is almost complete, with 6 years and 6 months missing. Due to technical issues and the change in archiving system, the simulation was suspended for some months but is expected to be completed by the end of the year.

Results from the previous reporting periods demonstrated that the higher-resolution simulations show improved agreement with observations (eOBS) and reanalysis data (ERA5) for temperature and precipitation (Fig. 3 and 4). Especially for precipitation, comparisons of daily precipitation over Central Europe in 2024 (Fig. 4) indicate that COSMO-CLM captures both the variability and magnitude of precipitation more realistically than the driving global ECHAM simulations, which tend to underestimate summer precipitation. This improvement becomes particularly evident when examining high-impact events. For instance, the Boris storm occurring between 12–16 September 2024 is represented in both model configurations. However, COSMO-CLM provides a spatial distribution of precipitation that is much closer to reanalysis data. This suggests that the regional storylines not only refine the overall climatology but also substantially improve the realism of individual extreme events, strengthening their suitability for event-based attribution studies, especially for precipitation extremes.

The dataset has already been applied for the study of high-impact storms (Ylenia, Zeynep, Antonia) in the German Bright (de L. L. de Amorim, under review). Here, we demonstrate the potential use of the regional storyline dataset, showing the storm intensification and changes in wind direction with global warming under a nudged (SN), free running (NSN) and a combination of both (SN_NSN).

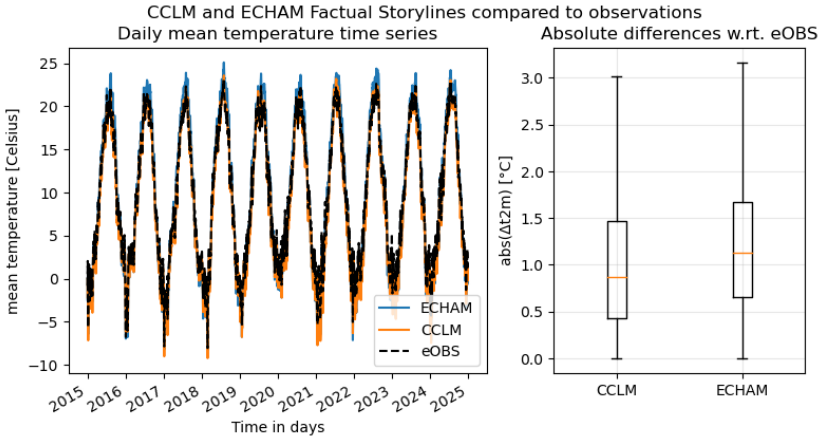


Figure 3: (left) CCLM and ECHAM daily mean temperature compared to eOBS.; (right) absolute daily mean temperature differences between regional and global storylines with respect to eOBS.

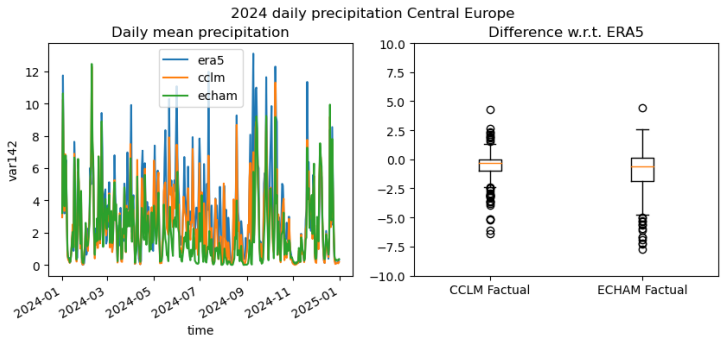


Figure 4: (left) CCLM and ECHAM daily cumulative precipitation compared to ERA5; (right) Absolute daily cumulative precipitation differences between regional and global storylines with respect to ERA5.

2.2 Project related publications:

de L. L. de Amorim, F., Feser, F., and Weisse, R. (under review) Intensification of a European Storm Cluster in a Warmer Climate: Evidence from Regional Storylines, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-5306.

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.

Lemburg, A., Fink, A. H., Lima, M. M., & Pinto, J. G. (2026a). Lagrangian analysis of two flavours of Central European heatwaves: Formation under omega blocking versus initiation by subtropical ridges. Quarterly Journal of the Royal Meteorological Society

Lemburg, A., Lima, M. M., Barpanda, P., Dillerup, I., Feser, F., Fink, A. H, León-FonFay, D., & Pinto, J. G. (2026b). Projected future changes in Omega blocking and subtropical ridges and their relationship to European heatwaves in two SMILEs, submitted to Quarterly Journal of the Royal Meteorological Society

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)

León-FonFay, D., Schachtschneider, R., van Garderen, L., & Feser, F., 2026b: A country-level storyline attribution of global warming on heat-related extremes in south america. Weather and Climate Extremes, 100961. https://doi.org/10.1016/j.wace.2026.100961

León-FonFay, D., Shepherd, T. G., van Garderen, L., and Feser, F. (under review) WCD Ideas: The transition from event-based storylines to conditional climate trajectories, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-5459.

van Garderen, L., León-FonFay, D., Dietz, V., van de Berg, W. J., Feser, F. (under review). Storyline attribution of fire weather during the 2025 Mediterranean summer. Communications Earth and Environment. Preprint available at https://doi.org/10.21203/rs.3.rs-9252889/v1

3. Module A – A6 CyclEx

Subproject: A6: Intensity and structural changes of extreme mid-latitude cyclones 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 November 2025 – October 2026

CyclEx investigates the changes in the intensities of extreme mid-latitude cyclones in a warming climate and uncertainties related with the representation of diabatic processes. The general idea of the project is to answer the question: how would a similar windstorm with the same dynamics look like in a different/warmer climate, and how large are the expected impacts. For this we used a storyline approach where we simulated recent extreme windstorm events with a spectral nudging approach.

Our storyline experiments include case studies of various windstorms from the period 2014–2024 for which we downscaled global climate model data that was nudged towards the large-scale dynamics of ERA5 (Hersbach et al. 2020).

We apply the pseudo-global warming approach, as described by Sánchez-Benítez et al. (2019) and Klimiuk et al. (2025), but with stronger nudging towards the ERA5 dynamics as the stronger nudging was shown to perform better in representing the storms. Pre-industrial (PI, 0K), present-day (Pres, +1.4K), and warmer (+3K) climate global storylines were available.

In the reporting period 20 storms were episodically dynamically downscaled with ICON using the global storylines as initial and boundary conditions for the 3 global warming levels and ERA5 as reference. We used the ICON-CLM setup with a resolution of 11 km to simulate recent storms within a regional domain covering the eastern North Atlantic and Central Europe (50° E to 60° W, 30° S to 70° N). Further, with the pressure tendency equation approach (Fink et al. 2012) processes contributing to cyclone intensification were quantified.

Results of peak intensity, mean accumulated precipitation and 10m gusts per storm are shown in Fig. 5. While no systematic change in intensity emerges when averaging across the 20 cyclones across the PI, Pres, and 3K simulations, an increase in gusts and wind speed is indicated but not significant, and precipitation consistently increases towards warmer climates. A substantial case-to-case variability demonstrates that individual cyclones respond differently, highlighting the importance of considering multiple cases to capture the range of possible changes.

Moreover, we find increased absolute diabatic heating contributions to cyclone intensification towards warmer storylines, while the relative contribution of diabatic heating remains constant on average. However, cyclones with lower diabatic heating contributions in the Pres simulations tend to become more diabatically influenced in the 3K simulations.

Increased precipitation is closely linked to increased diabatic heating, and this relationship is stronger in the 3K simulations, indicating that diabatic processes become more important. Wind speed and 10m gusts, on the other hand, are more closely linked to changes in relative vorticity than to diabatic heating directly. Core pressure changes are related to a combination of both diabatic heating and temperature advection (not shown). Consequently, there is not just one single physical process controlling changes in cyclone intensity and impacts across the different storylines.

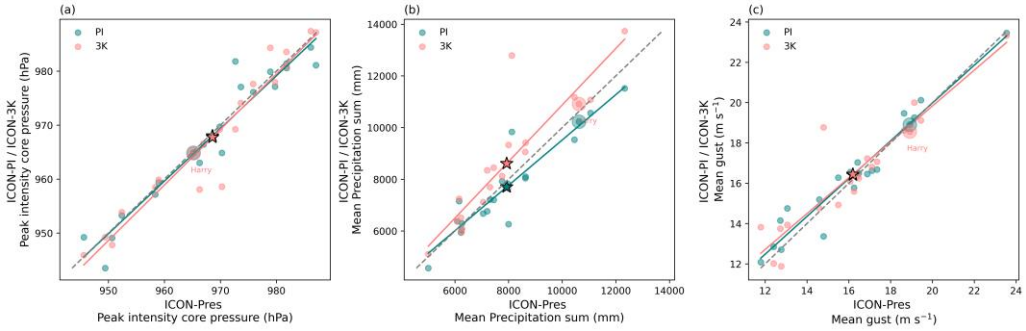


Figure 5: (a) Peak intensity core pressure (in hPa), (b) mean accumulated precipitation (in mm), (c) averaged 10 m gust (in m s−2), mean across all cyclones (star), and linear regressions (lines). All variables but peak intensity within the intensification phase from -30 h to 0 h, and all variables are averaged 600 km around the cyclone center but peak intensity.

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 2026 – October 2026

Rare-event sampling heat summer simulations

We used the rare-event sampling technique to simulate extremely hot summers in western Europe with the fully coupled Earth system model CESM2. The experiments were run for a current climate state and for pre-industrial climate. A publication based on these simulations has recently been published (Pfleiderer et al. 2026).

Summer seasons with extremely low North Atlantic Eddy Kinetic Energy

We investigated North Atlantic summers with extremely low eddy kinetic energy (EKE) using extreme cases from the CESM2 large ensemble and implemented a rare event-sampling workflow targeting low-EKE seasons. After solving technical challenges related to the estimation of EKE in short simulation segments, we created ensembles with extremely low EKE over the North Atlantic. Due to parental leave of Magdalena Mittermeier, this project had to be paused and no final analysis is available. We hope to take it up towards the end of the year within another project.

Nudged circulation storyline experiments with CESM2

We have run several nudged circulation storyline experiments with CESM2, in which we prescribe the horizontal winds to reanalysis under different forcing scenarios. These simulations are used by us to for attribution studies on the European drying trend (Dunkl et al. 2026), floods (Miersch et al. 2026), burned area, and several Master's theses.

4.2 Project related publications:

Dunkl, I., Bastos, A., & Sippel, S. (2026). European summer drying largely driven by atmospheric circulation changes since the 1980s. Nature Geoscience, 19(8), 914–921. https://doi.org/10.1038/s41561-026-02050-w

Miersch, P., Dunkl, I., Sánchez-Benítez, A., Athanase, M., Rakovec, O., Klotz, D., Sippel, S., Goessling, H., Zscheischler, J. (2026, accepted). Evidence from 2024 Storm Boris indicates anthropogenic climate change amplifies floods more than extreme precipitation, Science Advances.

Pfleiderer, P., Noyelle, R., Sippel, S. (2026). Heat Extremes Within Hot Summer Seasons Intensify More Than in Average Summers Under Global Warming. Earth's Future, 14, e2026EF008241. https://doi.org/10.1029/2026EF008241

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 2026 – October 2026

As outlined in the proposal for this period, no additional model simulations were performed during the reporting period. Simulations which were performed in previous reporting periods (or third-party simulations) thus form the basis of the analysis. Recall that project XPreCCC is based on Lagrangian analysis of high-resolution model simulations.

The Lagrangian tracking algorithm developed by the project (Meredith et al., 2023) was applied to a set of transient convection-permitting climate simulations over Germany (Rybka et al., 2023), with a view to examining the warming response of convective precipitation conditional on the strength of the synoptic forcing, e.g., convection based on large-scale uplift (strong forcing) or airmass convection (weak forcing). Analysis looked at various object-oriented properties, such as mean intensity, area and the number of objects. The warming responses of various object properties were found to vary non-linearly with the strength of the synoptic forcing. One example is the changes in total convective precipitation, mean object volume and the number of objects.

In a previous report, convection-permitting ensemble sensitivity simulations of a 10-day period of unusually high convective activity over Germany during summer 2016 (Piper et al., 2016) were described. Ensembles of the event were created for present and future climates using the pseudo global warming (PGW) technique (Schär et al., 1996). Importantly, future ensembles based on a vertically constant warming profile and a warming profile with a strong vertical gradient were produced. These served as the basis of Lagrangian analyses of convective precipitation, in which the changes were compared between the two ensembles, while also taking account of the strength of the synoptic forcing. It was found that changes in the convective precipitation and its characteristics were sensitive to both the vertical warming profile and the strength of the synoptic forcing (Fig. 6), for example the number of convective objects and their intensity.

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

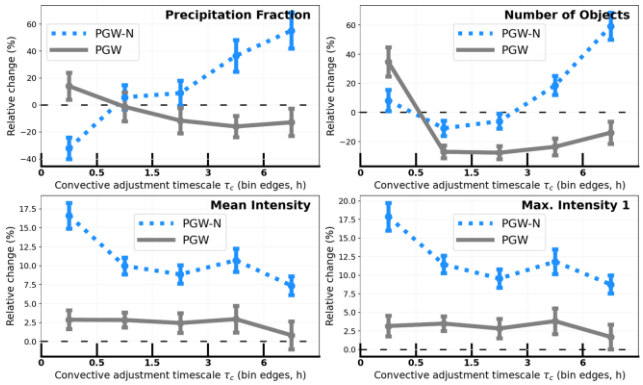


Figure 6: Climate change signal of convective precipitation conditional on the strength of the synoptic forcing (x-axis) and the vertical warming gradient (blue/grey curves). The strength of the synoptic forcing is determined based on the convective adjustment timescale (Done et al., 2006), with low values corresponding to a strong synoptic forcing and high values to a weak. The blue curve (PGW-N) represents a neutral warming profile, i.e., vertically homogeneous, while the grey curve (PGW) represents a warming profile with a positive vertical gradient.

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 B – B3.7 DySyTEx

Subproject: B3.7: Dynamical system perspective on weather regimes and temperature extremes in a changing climate
Subproject leader: Joaquim G. Pinto[1], Sebastian Buschow[2]
1) Institute of Meteorology and Climate Research - Tropospheric Research (IMKTRO), Karlsruhe Institute for Technology (KIT), Karlsruhe
2) University of Bonn, Bonn

6.1 Usage report November 2025 – October 2026

DySyTex investigates the characteristics and changes of European heatwaves, in particular the atmospheric circulation associated with them. The circulation is characterized by combining weather regimes with dynamical systems metrics. The work packages were restructured so that all analyses based on ERA5 are completed first, followed by the analysis of the climate model ensembles.

Since the start of the project in 2024, heatwaves from May to September in ERA5 and their link to weather regimes and dynamical systems metrics have been analyzed, using the HWMId plugin for heatwave detection (Russo et al, 2015). The results show that the circulation on heatwave days is more persistent than usual only in July and August, related to more frequent Scandinavian and European blocking. Throughout the season, the link between circulation and temperature is anomalously strong on heatwave days. The revision of the corresponding publication was completed in early 2026 (Dillerup et al., 2026a).

As a refinement, recurrent heatwaves in ERA5 and their associated circulation were investigated across multiple spatial scales using an object-tracking algorithm (Fig. 7). Recurrence shows distinct characteristics at the local scale, at the scale of heatwave objects (where it is linked to weather regimes), and at the continental scale. Recurrent heatwaves tend to be preconditioned by preceding ones through soil moisture depletion, which partly leads to higher temperatures. A manuscript has been submitted and is currently under revision (Dillerup et al., 2026b).

In addition, the analysis of future changes in heatwaves and atmospheric circulation in the MPI-GE and SMHI-LENS large ensembles has begun. So far, heatwaves have been detected in all 50 members per model, and data processing for dynamical system metrics (Faranda et al, 2024) and weather regimes (Grams et al, 2017) have begun for selected global warming levels.

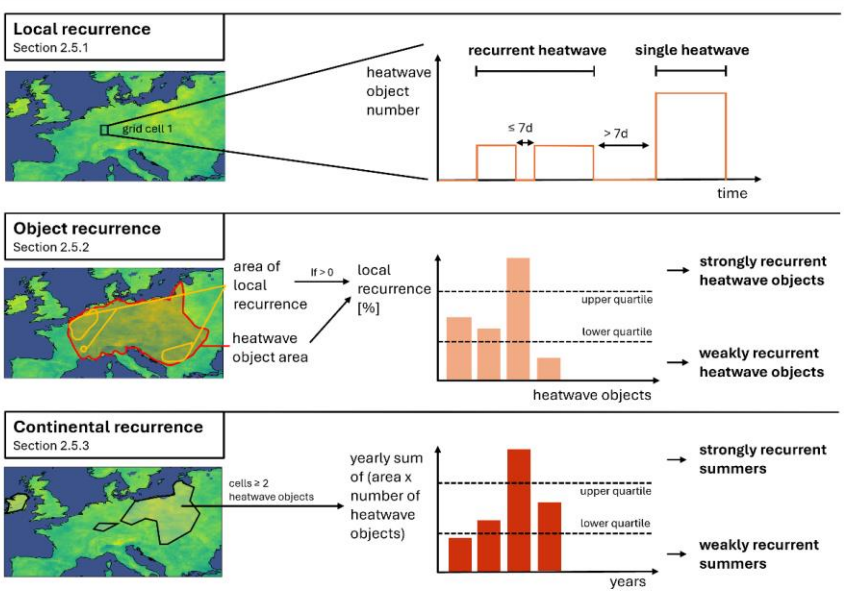


Figure 7: Schematic representation of the methodology developed to investigate recurrent heatwaves at several spatial scales. The top panel shows the definition of local recurrent heatwaves per grid cell, based on a maximum break criterion between successive heatwaves. The middle panel links these grid-cell heatwaves to larger-scale heatwave objects, i.e., heatwave regions tracked over time, by requiring a minimum fraction of the object's area to be affected by recurrence. The bottom panel shows the continental scale, which considers repeated heat exposure per grid cell and distinguishes summers with high and low heatwave recurrence.

6.2 Project related publications:

Dillerup, I., Lemburg, A., Buschow, S., and Pinto, J. G.: Dynamical system metrics and weather regimes explain the seasonally-varying link between European heatwaves and the large-scale atmospheric circulation, Earth Syst. Dynam., 17, 265–289, https://doi.org/10.5194/esd-17-265-2026, 2026a.

Dillerup, I., Messori, G., Lemburg, A., Buschow, S., and Pinto, J. G.: How atmospheric and surface conditions shape recurrent heatwaves in Europe: From local to continental scales, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2026-2453, 2026b.

7. Module C – C3 CROP4EUROPE

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

7.1 Usage report November 2025 – October 2026

During the reporting period, the allocated resources were mainly used to assess the future evolution of climate drivers relevant for European grain maize impacts. As reported previously, tensor generalized canonical correlation analysis (TGCCA) was applied to identify large-scale drivers of crop heat and water stress. Heat stress was represented by the Heat Magnitude Day (HMD; Zampieri et. al 2017), while water stress was described by a nonparametric version of the Standardized Precipitation Evapotranspiration Index (NPSPEI; Vicente-Serrano et al. 2010). The analysis covered February–November, including the main growing season (May–November) as well as the preceding months to account for potential preconditioning effects.

Using E-OBS data, the analysis identified widespread heat and dry conditions across Europe as the dominant impact pattern (Fig. 8a–b). The joint seasonal contributions of HMD and NPSPEI is strongest during June–August (Fig. 8c–d) associated with hot and dry summers. Their temporal evolution also indicates a significant increase in heat and drying, particularly since the 1980s (not shown). These results were obtained during the previous reporting period. In the current period, we investigated how these patterns evolve in E-OBS based bias-corrected EURO-CORDEX simulations (Dosio 2016) for 1981–2040.

For this purpose, the TGCCA patterns derived from E-OBS were projected onto each EURO-CORDEX ensemble member. This provides a time series describing the evolution of the observed heat and dryness patterns in each simulation. The results are shown in Fig. 8e–f. All ensemble members reproduce an increasing HMD signal (Fig. 8e), whereas none reproduce the observed drying trend in NPSPEI (Fig. 8f). Indeed, no significant NPSPEI trend was detected for any ensemble member based on a Mann–Kendall test.

As an additional robustness check for the absence of these drying trends, spatial trends of NPSPEI were analyzed directly. Annual values were calculated at each grid point using the seasonal weights shown in Fig. 8d. Linear trends were then estimated grid-point wise for E-OBS and each ensemble member, and the significance of the regression slopes was assessed using a two-sided Student's t-test. The results confirm the TGCCA-based findings: the observed drying trend is not reproduced by the EURO-CORDEX simulations, and some ensemble members even show significant increases in wetness. In contrast, the observed increase in HMD is consistently reproduced.

Similar analyses were performed using the CEU-3i simulations (Braun et al. 2026), but are not shown here for space reasons. Increasing HMD was reproduced by all models, whereas only two of the eight models showed a drying signal in NPSPEI. Thus, although some models reproduce a drying trend, agreement across the ensemble remains limited. Since drying is an important component of compound heat–drought stress, its weak representation in the climate-model simulations may lead to an incomplete assessment of future crop impacts.

In addition, the XCES Freva plugin “Crop Impact Drivers” was completed during the reporting period. The plugin implements the TGCCA framework developed within the project for analyzing climate drivers of crop impacts. Lastly, an article on the crop model emulator developed during the previous reporting periods has been submitted.

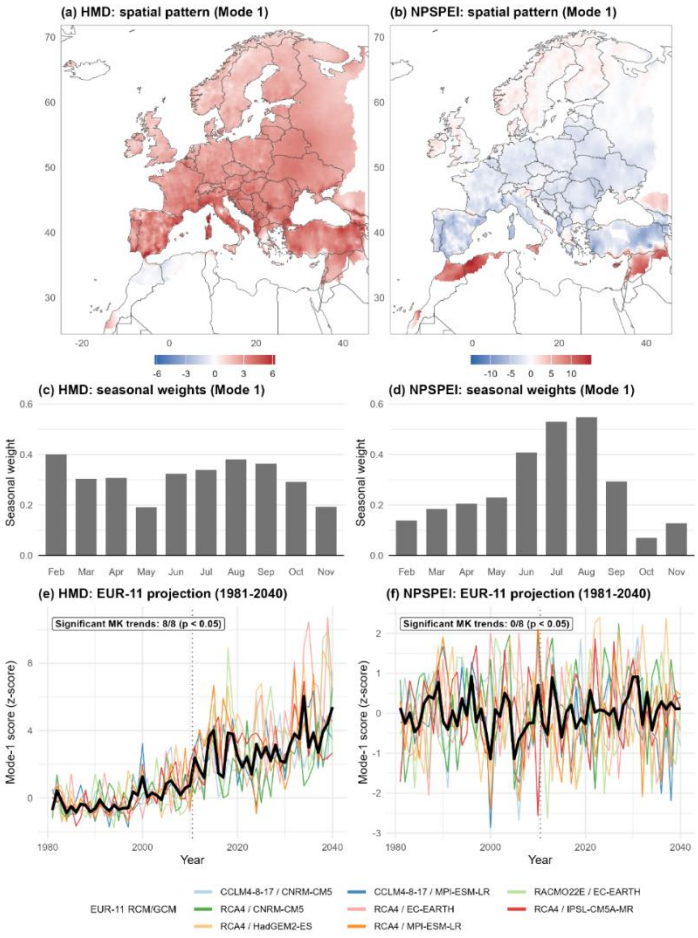


Figure 8: TGCCA Mode 1 results for HMD and NPSPEI. Panels (a–b) show the E-OBS-derived spatial patterns and panels (c–d) show the corresponding seasonal weights from February to November. Panels (e–f) show the z-score standardized Mode 1 scores obtained by projecting these patterns onto the bias-corrected EURO-CORDEX (EUR-11) simulations for 1981–2040. Colored lines represent individual RCM/GCM combinations and the black line shows the ensemble median. Mann–Kendall trends are significant at the 95 % confidence level for all eight HMD projections, whereas no significant trend is detected for NPSPEI. For HMD, z-scores were computed per grid cell and calendar month from the 1981–2010 reference period only.

8. 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

8.1 Usage report November 2025 – October 2026

Building on the extensive simulation campaign conducted in 2025, the computational work on Levante primarily involved rerunning selected hydrological and hydrodynamic simulations and checking the consistency of the existing modelling framework. Particular attention was given to the RIM2D two-dimensional hydrodynamic model, which enables high-resolution flood inundation simulations using GPU-accelerated computing. These activities supported the verification and reproducibility of the modelling workflow and the consistency of the simulation datasets used for the flood impact attribution analysis.

The existing simulation framework provides the basis for the ongoing assessment of flood characteristics across different climatic conditions, including peak discharge, inundation extent, inundation depth, and damage-related indicators. The remaining project activities will focus on further evaluation of the simulation outputs, additional model runs where necessary, and consolidation of the results for the final attribution analysis.

The Levante infrastructure at DKRZ continues to provide an important computational environment for these activities, particularly for GPU-based hydrodynamic simulations and the processing of large simulation datasets.

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.

9. Module C – C12 HailClim

Subproject: Assessing the Impact of Hailstorms in a Future Climate
Subproject leader: Michael Kunz, Susanna Mohr, Jannik Wilhelm
Institute of Meteorology and Climate Research - Tropospheric Research (IMKTRO), Karlsruhe Institute of Technology (KIT), Karlsruhe

9.1 Usage report November 2025 – October 2026

The objective of the HailClim subproject is to quantify the impacts of hail events under both historical and future climate conditions. Based on potential hail tracks derived from three-dimensional radar data provided by the German Meteorological Service (Deutscher Wetterdienst, DWD), the atmospheric environmental conditions relevant to hail formation were characterized and analyzed using ERA5 reanalysis data. Building on these analyses, a statistical model was developed to predict the frequency of hail days. The model is based on the decision-tree-based XGBoost algorithm and enables the quantification of hail days as a function of various atmospheric parameters relevant to convection. The developed model was applied to corresponding parameters derived from various climate simulations and scenarios. This approach allows changes in hail frequency under future climate conditions to be quantified.

The required convection-relevant parameters were derived from meteorological variables obtained from the NUKLEUS ensemble simulations available on Levante, using the R package thundeR (Taszarek et al., 2024). thundeR is a powerful post-processing tool that enables the efficient calculation of numerous thermodynamic and kinematic parameters (more than 200) from atmospheric profiles. Thanks to its efficient C++ implementation, the computational time required per profile can be substantially reduced, allowing large datasets to be processed.

Eight different climate simulations were considered: EC-Earth, MPI-ESM, and MIROC6, each dynamically downscaled using ICON-CLM and COSMO-CLM. For the EC-Earth–ICON-CLM combination, the SSP2-4.5 and SSP5-8.5 scenarios are also available in addition to the SSP3-7.0 emissions scenario. Based on the calculated convective parameters from these simulations, we were able to estimate changes in hail frequency under a warmer future climate for each model and systematically analyze the differences between the individual models. The ensemble mean across the climate simulations provides a robust estimate of future hail frequency (Fig. 9).

The Levante high-performance computing system was used primarily for the computationally intensive preprocessing step, namely the derivation of convection-relevant parameters. The subsequent modeling was performed on separate computing infrastructure, where the XGBoost model was developed. Overall, applying thundeR generated approximately 9 TB of data files per climate simulation. Once each simulation had been

completed, the corresponding files were transferred to the separate infrastructure. This infrastructure will also be used for further project activities, such as developing a hail risk model to estimate future damage resulting from changes in hail frequency. Consequently, no additional computing resources or storage capacity on Levante will be required.

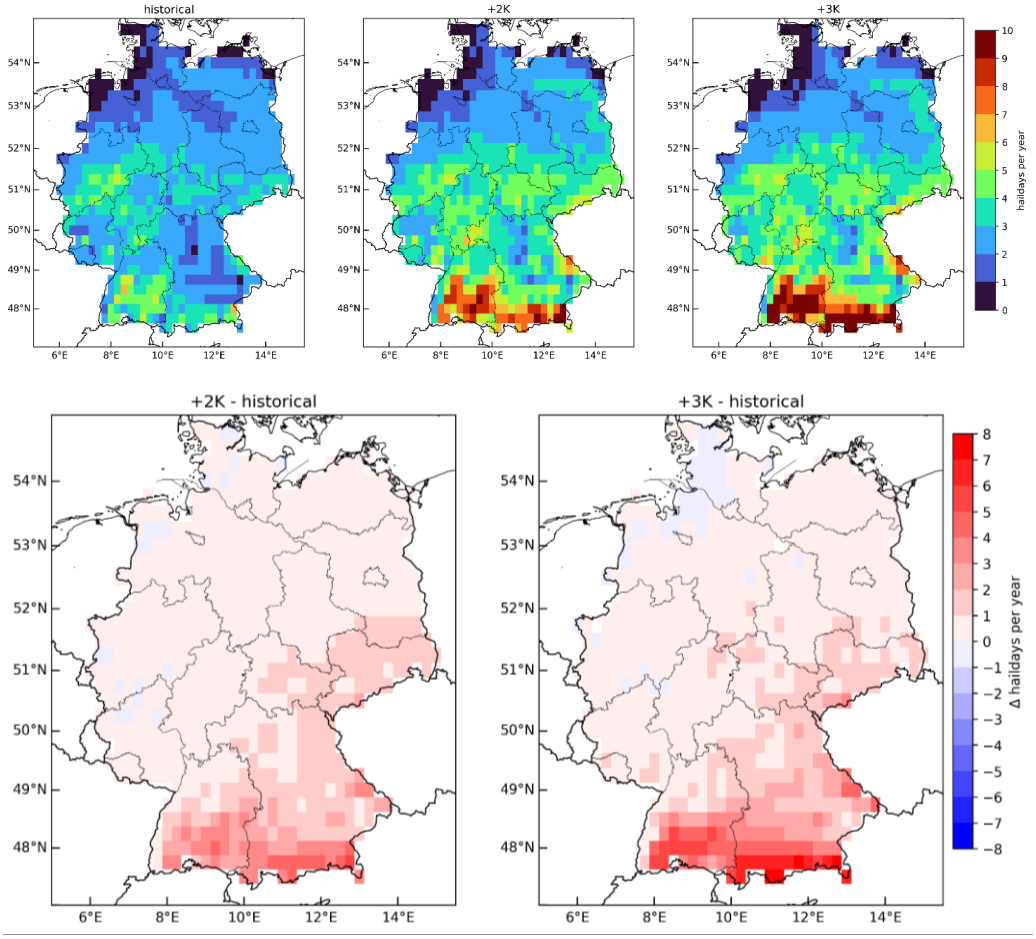


Figure 9: Frequency of annual hail days (median of all eight simulations) for historical period (1961 – 1990), +2K and +3K period (top). Difference between historical and +2K (bottom left) as well as historical and +3K (bottom right).

10. Module D – CoSoDaX

Subproject: bb1159 (D1/D2): Coordination of software and data management for ClimXtreme
Subproject leader: Torben Kunz[1], Etor Lucio-Eceiza[2], Deborah Niermann[1]
1) Deutscher Wetterdienst Offenbach, 2) Deutsches Klimarechenzentrum Hamburg (DKRZ)

10.1 Usage report May 2026 – October 2026

Module D is a supporting module of the ClimXtreme research project. It coordinates software and data management (CoSoDaX), in particular the development and operation of the ClimXtreme Central Evaluation System (XCES [1]); the provision and analysis of core datasets for evaluating climate extremes; support for software developments for extreme-event research; and maintenance of existing software.

XCES is based on Freva (Kadow et al., 2021), a scientific software framework for high-performance computing. Freva provides a standardized climate-model database, programming interfaces, and a record of evaluations, and is maintained and further developed by the Climate Informatics and Technologies (CLINT [2]) group at DKRZ.

One of Module D's primary objectives is to establish a suitable common data basis for the joint project, accessible through XCES. Building on data from the former MiKlip project [3], this collection was progressively expanded during

the first ClimXtreme phase. In the current phase, the focus is primarily on providing near-real-time data, resulting in continually growing storage requirements to keep data holdings up to date.

Although the large majority of data are linked from /pool/data, a substantial volume is hosted within joint project bm1159 (approximately 270 TiB). Fig. 10 (left) provides an overview of the data types integrated into the system and hosted using bm1159 resources (the joint project of main project bb1152). Almost all available workspace storage is currently in use: 325 of 345 TiB (94%).

Data available through /pool/data, including CMIP6 and CORDEX, are crawled and indexed into XCES weekly to keep the Databrowser as current as possible. In addition, specialized datasets—including HYRAS-DE1km (v6.1), five-minute RADOLAN data, and ERA5—are updated daily or every second day, respectively, including standardization and metadata crawling. These routines are scheduled through scrontab and use a considerable share of the project's computing resources (approximately 30%). The standardized ERA5 data are also used by Freva sister instances (RegIKlim, GEMS, CODES, and Freva) and by a broader DKRZ user community.

Scientific analysis of the uncertainty in climatological averages of threshold days—including hot, summer, frost, and ice days—in HYRAS-DE1km (tasmin, tasmax) is ongoing. In addition, post-processing and indexing of near-real-time RADOLAN-YW data at five-minute resolution started during this reporting period and are now carried out daily. Provision of ERA5-Land data also began during the reporting period (July–August). However, neither its production nor hosting uses ClimXtreme project resources (bm1159/bb1152): the data are available through waterpark.dkrz.de as HEALPix data (Górski et al., 2005) via S3 (Fig. 10, right).

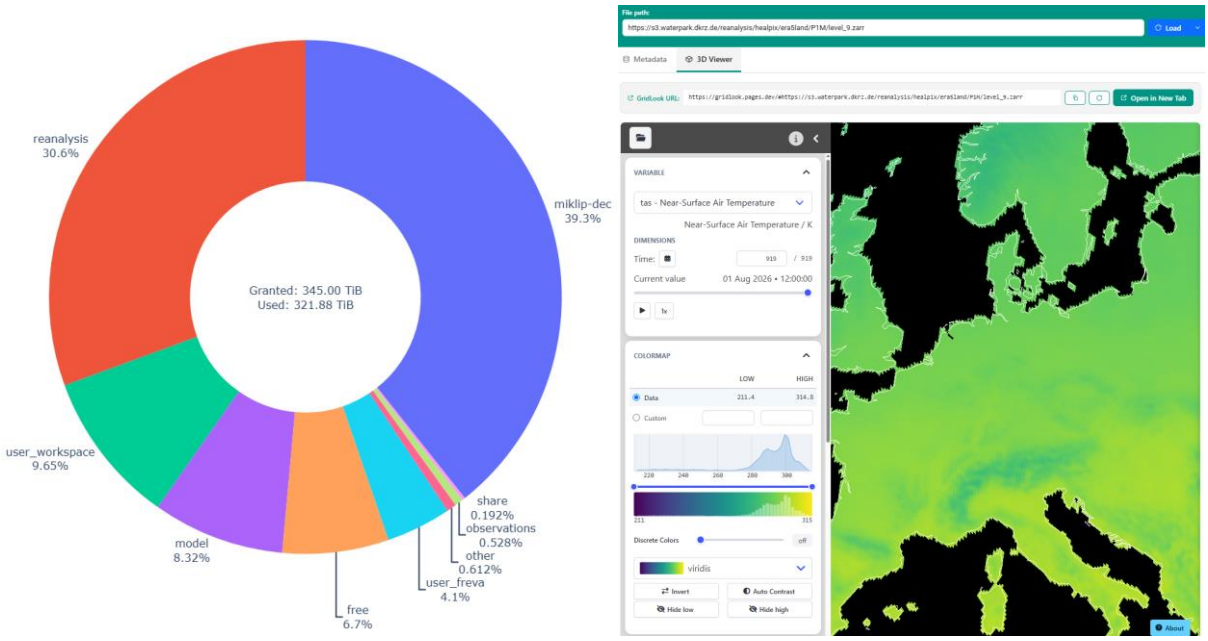


Figure 10: (left) Storage demand (TiB) of different data types under /work/bm1159/XCES/, hosted by the ClimXtreme project bm1159, and their relative shares; (right) near-surface air temperature in ERA5-Land at HEALPix level 9, provided through waterpark.dkrz.de

XCES enables flexible integration of verification routines (plugins). These analysis tools are developed by Modules A–C with support from Module D, or directly by Module D, to address project needs and make methods available to the whole consortium. Six plugins have been developed during ClimXtreme Phase 2, while a further 12 are at different development stages (Tab. 2). In addition, 24 plugins were inherited from the first ClimXtreme phase, the former MiKlip project, or the RegIKlim sister project.

These plugins are hosted and run through XCES and are available to the entire ClimXtreme community. During the period November 2025–October 2026, approximately 11,200 plugin calls were made, including 7,700 since May 2026. The storage allocated to outputs has also grown steadily. XCES users currently occupy more than 47 TiB through plugin outputs, data indexed back into XCES, and their personal workspace.

Table 2: Plugins developed during ClimXtreme Phase 2. Asterisks indicate plugins not yet centrally integrated into XCES and at different stages of development.

plugin	description	project
CROP	Impact of extreme events on crops	C3
PCA	principal component analysis based on xeofs	B1.1/B3.7
PrecipReturnPeriodMaps	maps of precipitation sums and return periods	COO
PredictBuildingDamage	maps loss ratio exceedance probabilities for building damage	COO
SECSF	Crop-yield emulation with SECSF surrogate model.	C03
Trendtest	linear trends with significance test	B1.1/B3.7
Analogues*	analysis of circulation analogues	B1.1/B3.7
Dacollector*	data preparation	B1.1/B3.7
Dsmetrics*	Dynamical system metrics	B1.1/B3.7
Dualtrees2d*	2d wavelet transforms	B1.1/B3.7
FloodExtent*	Identification of areas affected by fluvial flooding	C05
Markov_attribution*	Impact of extreme events on crops	B1.1
Regional_hwmid*	Successor of HWMID	B3.7
SLBM*	GEV distribution of sliding block maxima	B3.7
Sousa_blocking*	Atmospheric blockings	A5
SPEI*	Drought indices SPI and SPEI	B1.1/B3.7
TGCCA*	TGCCA on climate and crop-growth drivers	C3
TLSW*	Smooth trend autocovariance functions via wavelets	B1.1/B3.7

Total CPU use—including data standardization, plugin development and bug fixing, and analysis runs—amounted to approximately 5,453 node-hours (so far). This corresponds to around 80.6% of the resources allocated for the full year 2026, or 96.7% of the resources available up to the time of reporting. Note, that the originally granted share for bm1159 turned out to be insufficient for operational demand and, therefore, node-hours had to be transferred from the main project bb1152 during the year.

An adjacent CLINT research activity focuses on applying AI/ML methods (Kadow et al., 2020) to climate-science questions, with direct usability through XCES—particularly through data provision and plugins—in mind. The research group has further developed these methods using HLRE-4 GPU resources. Other ClimXtreme Freva plugin developers have likewise used project computing resources for plugin development and analysis. Note that originally no GPU node-hours were allocated to bm1159 for 2026. All GPU resources used for these activities were transferred from the main project bb1152.

No archive storage has been used so far, although 135 TiB were granted for this purpose. As Module D provides shared software and data services, decisions on retaining, deleting, or archiving data cannot be made solely by the

operating team. The data are used not only by plugin users but also by other ClimXtreme scientists and by other sister projects and general DKRZ users. Since part of the data needs to be available until the end of the project and perhaps beyond, Module D is therefore coordinating a data triage to identify data that can be removed, data that must remain readily accessible either under this or other projects, and data suitable for transfer to archive storage.

11. 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.

Done, J. M., et al. (2006). Mesoscale simulations of organized convection: Importance of convective equilibrium, Quarterly Journal of the Royal Meteorological Society, 132, 737–756, https://doi.org/10.1256/qj.04.84.

Faranda, D., Messori, G., Alberti, T., Alvarez-Castro, C., Caby, T., Cavicchia, L., Coppola, E., Donner, R. V., Dubrulle, B., Galfi, V. M., Holmberg, E., Lembo, V., Noyelle, R., Yiou, P., Spagnolo, B., Valenti, D., Vaienti, S., & Wormell, C. (2024). Statistical physics and dynamical systems perspectives on geophysical extreme events. Physical Review E, 110(4). https://doi.org/10.1103/physreve.110.041001.

Górski, K. M., Hivon, E., Banday, A. J., Wandelt, B. D., Hansen, F. K., Reinecke, M., & Bartelmann, M. (2005). HEALPix: A framework for high-resolution discretization and fast analysis of data distributed on the sphere. The Astrophysical Journal, 622(2), 759–771. https://doi.org/10.1086/427976.

Grams, C. M., Beerli, R., Pfenninger, S., Staffell, I., & Wernli, H. (2017). Balancing Europe's wind-power output through spatial deployment informed by weather regimes. Nature Climate Change, 7(8), 557–562. https://doi.org/10.1038/nclimate3338.

Hersbach, H. et al. (2020): The ERA5 global reanalysis, Q. J. Roy. Meteorol. Soc., 146, 1999–2049, https://doi.org/10.1002/qj.3803.

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).

Klimiuk, T. et al. (2025): The European summer heatwave of 2019—a regional storyline perspective. Earth Syst. Dyn. 16, 239–255, https://doi.org/10.5194/esd-16-239-2025.

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.

Russo, S., Sillmann, J., and Fischer, E. M. (2015): Top ten European heatwaves since 1950 and their occurrence in the coming decades, Environmental Research Letters, 10, 124 003, https://doi.org/10.1088/1748-9326/10/12/124003, 2015

Rybka, H., et al. (2023). Convection-permitting climate simulations with COSMO-CLM for Germany: Analysis of present and future daily and sub-daily extreme precipitation, Meteorologische Zeitschrift, 32, 91–111, https://doi.org/10.1127/metz/2022/1147.

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.

Taszarek, M., Czernecki, B., Szuster, P. (2024): ThundeR – A rawinsonde package for processing convective parameters and visualizing atmospheric profiles. In 11th European Conference on Severe Storms, doi: 10.5194/ecss2023-28

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.

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

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

[3] https://www.fona-miklip.de/