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Past and future European atmospheric extreme events under climate change – the *ClimXtreme* program's structure and results

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Abstract. The meteorological extreme events heatwaves, droughts, heavy precipitation, floods and wind storms affect socio-economic systems and generate considerable attention. The role of anthropogenic climate change in the generation, frequency, and severity of observed and future events triggers mitigation and adaptation questions. Weather-related extremes are rare and embedded into atmospheric dynamics. This sets the frame for a dynamical-statistical analysis coupled to detailed impact or risk studies of rare events. This approach is taken by the German Federal Ministry BMBF/BMBFTR funded project *ClimXtreme-1* with 35 sub-projects. Here we compile the contributions of 21 articles of the inter-journal NHESS/ASCMO/WCD special issue. We connect them to 33 peer reviewed *ClimXtreme-1* writings in other journals. For archetypic events over continental areas in mid Europe the individual research results are reported. These involve the use of existing and newly developed indices, analyses of the atmospheric dynamics and process-based chains using global and regional climate models results and statistical detection and attribution studies, with emphasis on establishing a causal relationship between extreme events and anthropogenic climate change. Two overarching conclusions emerge from the joint appraisal of the *ClimXtreme-1* publications. Firstly, conclusions on causality show that the attribution analyses of observed events demonstrate the necessary contribution of past anthropogenic climate change to the event while sufficient contributions to future extremes need to be established. Secondly, findings from the dynamic process studies highlight the need to expand the current attribution approaches (statistical vs. storyline) to include the mediator-moderator framework.

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1 Introduction

1.1 Scientific Background

Weather-related extreme events like heatwaves, droughts, heavy precipitation, floods and wind storms regularly affect the mid-latitudes and generate considerable public and policy attention. Among the topics raised is the question on the role that anthropogenic climate change plays in the generation, frequency, and severity of these events, followed by a debate about how society can better protect itself in the future. Consequently, the relevant questions that are also raised in the various IPCC assessment reports and posed in the public media and by politicians are:

- Has past climate change increased the frequency and/or severity of extreme weather events?
- Will future climate change modify the occurrence of extreme weather events?

Sometimes it is possible to derive some simple answers to these questions from observational data and model reanalyses for the past, as well as climate model projections for the past, present and future. Nevertheless, a more thorough examination of the scientific underpinnings of the problem, that is to say, the causal relationships between climate change, weather-related extreme events and their impacts, reveals that overly simplistic and inadequate responses will be incapable of providing effective guidance or sound knowledge-based decisions in the face of such events.

The search for suitable approaches to assess changes in extremes immediately faces the most important open scientific questions regarding the definition of extreme events (i.e. attributes such as type, extent, severity or impact), the process-based causal chains (e.g. non-linear interacting processes that cause weather extremes as greenhouse gases concentrations rise) and the statistical uncertainty of quantitative measures to describe changes.

Due to their complexity, the definition of extreme events and their risk management depend heavily on the problem at hand. Weather-related extremes are usually defined on the basis of threshold values, return periods or probability of occurrence (Risbey and Kandlikar, 2002; Bindoff et al., 2014). The choice of weather and climate variables or indices to characterize the extremes, their spatio-temporal extent or their structure and intensity are thus very relevant. The WCRP Expert Team on Climate Change Detection and Indices (ETCCDI) provides extreme indices that describe extremes at a fixed point in space. This Eulerian view is one way of looking at extremes. In a Lagrangian perspective, extreme events are defined by the positioning of trajectories outside their typical ranges in phase space or by extreme intensities along trajectories in physical space (Lucarini et al., 2012). On the impact and risk side, however, the vulnerability and exposure of the population or infrastructure to the hazard of the event, the communication plan and the prevention also play an important role in the definitions of extremes and thus for the conclusion regarding the attribution of causes (Philip et al., 2020; Van Oldenborgh et al., 2021). This relates to the WCRP definition of extreme events, which are generally viewed as high-impact events on land surfaces. It is therefore necessary to focus on weather-related extremes and/or rare events that have the potential to cause damage. These are defined as hazards. However, these hazards must also be identifiable and quantifiable through their underlying physical processes.

Another challenge is to identify the process-based causal chains between increasing greenhouse gas concentrations and extreme weather-related events. The climate system is a typical spatially extended system far away from a thermodynamic

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equilibrium. From statistical physics, it is known that such systems can produce large fluctuations on all scales of motion (Prigogine and Hiebert, 1982). Smaller scale extremes potentially develop while being embedded in large fluctuations on a larger scale in space and/or time (e.g. annual, decadal variability), or due to the occurrence of rare combinations of factors jointly leading to an extreme development (e.g., compound events). It is thus difficult to assess direct causality of possible changes in the generation, frequency and intensity of extreme events to anthropogenic forcing, since extremes have always occurred and are subject to physical constraints such as the conservation of masses, energy, and angular momentum. One of the key challenges is to quantify the enhanced role of diabatic processes in a warmer world, how they related to changes in the atmospheric circulation and its boundary conditions (e.g. sea surface temperature, sea ice) and if these changes do contribute - or do not - to more frequent and intense weather-related events.

The climate system is continuously driven by the net radiative imbalance between solar forcing and infrared cooling to space. Atmospheric flow is thus ultimately determined by the meridional contrasts of the Earth's net radiation balance. Extreme weather events such as torrential rains, severe squall lines, heatwaves, droughts and wind storms, are embedded in the complex, three-dimensional and temporally evolving atmospheric flow. Therefore, changes in the large-scale atmosphere-ocean-cryosphere environment and thus in the feedback within the climate system can lead to changes of atmospheric flow and other boundary conditions (e.g. sea surface temperature), which in turn may change the occurrence of meteorological extremes (Stephenson et al., 2008).

Usually the observed increase of global mean near-surface temperatures over the past two centuries is presented as the indicator of anthropogenic climate impact. Correspondingly, any change in extreme climate events on spatial scales shorter than the global and temporal scales smaller than the centennial is ultimately embedded into the changes of atmospheric greenhouse gas concentrations. For those, the global mean concentration of CO_2 is the leading indicator variable of anthropogenic forcing (Köhler et al., 2017). Its evolution over the past 150.000 years seen in Fig.(1) clearly shows that the recent concentration, and in particular its very steep increase in recent decades, are extreme by themselves.

Assessing the statistical uncertainty of quantitative measures of changes in weather-related extremes is a necessity for decision making, but imposes major difficulties. Decisions are usually made on the basis of a cost-benefit assessment, which requires not only the most accurate possible information about possible future conditions, but also its uncertainties and implications. This requires both mapping the relevant process-based chains of effects that lead to the damage from extreme events and assessing the associated uncertainties. For this purpose, statistical-dynamical methods must be transferred to practice in a meaningful way and new foundations of statistical risk modeling must be developed.

Weather-related extreme events are mostly related to meteorological rare events. This puts the statistical analysis away from standard normal distribution considerations into the framework of extreme value theory. When analyzing rare meteorological events that are defined by several variables in space and time, multivariate extreme value statistics becomes necessary, which then takes into account the spatio-temporal interactions of different variables. For example, the consideration of advective processes requires the analysis of four variables: three velocity fields and the advected tracer in their four-dimensional space-time environment. This is particularly important for compound events, which are multivariate by nature (Bevacqua et al., 2021).

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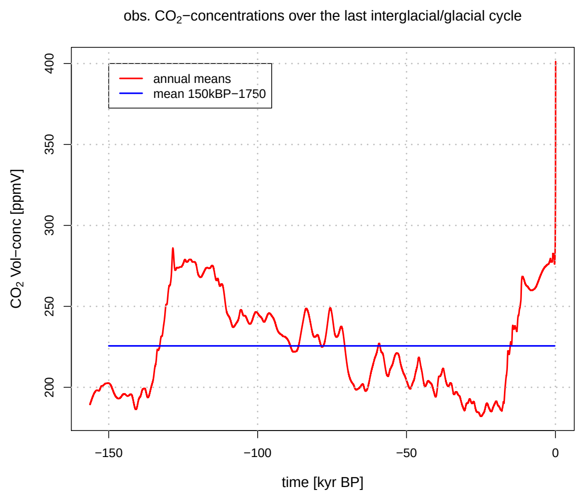

Figure 1. Global mean carbon dioxide concentrations over the past interglacial - glacial - holocene period (red), mean concentration before 1700 BC (blue). units in ppmV, data acc. to Köhler et al. (2017)

Lack-of-knowledge and thus uncertainty further arises due to sparsity of observational datasets in space and time. Finally, evaluation of statistical evidence and the assessment of causality are most essential in the relatively new field of single event attribution to climate change.

1.2 The *ClimXtreme* Project

The questions set above are addressed in the comprehensive, multi-institutional project *ClimXtreme*, which is funded by the German Federal Ministry of Forschung, Technologie und Raumfahrt (BMFTR, formerly German Federal Ministry of Education and Research, BMBF) from 2019 to 2026. The *ClimXtreme* research program is focused on the prototypical weather-related extreme events that have relevance for non-oceanic areas in Europe. It follows the characterization of hazard types compiled by the World Climate Research Program (WCRP) Grand Science Challenge "Understanding and Predicting Weather and Climate Extremes". This internationally coordinated research plan focuses on four archetypes of events relevant for weather extremes at European mid latitudes. These are heavy precipitation events, wind storms and severe convective storms, heatwaves and droughts. The overarching objective of *ClimXtreme* inspired by the WCRP Grand Science Challenges is to investigate the relationship between extreme weather events and their physical manifestations, as well as their impact on specific socio-economic systems.

The results of the initial phase of *ClimXtreme* (2019-2023) and associated research projects have been primarily disseminated through 21 peer-reviewed publications from the NHESS/ASCMO/WCD inter-journal special issue (SI). This set of publications is extended and supported by further 33 peer reviewed writings in other journals. The present cover publication aims to compile and summarize the individual contributions of the inter-journal SI, connect them with the remaining papers, to provide the

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relevant data, the joint results, and further emerging, overarching findings including the two central questions mentioned above. It shall serve as a reference publication to the forthcoming IPCC Seventh Assessment Report.

2 The *ClimXtreme* Research Approach

The research approach of *ClimXtreme*, being reflected by its publications inside and partly outside the Special Issue, and the contributions of the hazard specific working groups sections below, can be summarized along four main directions.

2.1 Knowledge about processes and their couplings causing extreme events

The central focus within *ClimXtreme* is the assessment and understanding of weather extremes under climate change. In contrast to the gradual changes of the mean of bulk climate statistics the view on individual events requires additional information because the causal relation between extreme events and large scale climate change is not as obvious as it is for the mean climate statistics. Further, extreme meteorological events contribute in a highly nonlinear way to climate change impacts on society and ecosystems. This once more underlines the necessity for the joint research on shorter and longer term changes of extreme events, to relate extremes to their impact which necessarily implies near surface processes, but also to connect the three dimensional free atmosphere dynamics and thermodynamics with its impact on near surface processes features. Especially this coupling between free atmosphere processes and extreme meteorological near surface events in connection with the causality question makes it necessary to introduce the concept of mediator and moderator processes (for definition see 2.4) which need to be distinguished and identified.

The general strategy for assessing the climate change aspects of impact relevant and rare meteorological events in Europe - also aiming at reducing related uncertainty - was achieved by improving the understanding of the physical processes in the atmosphere leading to extremes. This was accomplished through observational data analysis and climate system modeling in combination with appropriate statistics and measures of impact by extreme/rare weather events in quantifiable metrics. As an example, the effects of future sea ice retreat scenarios (part of the Arctic Amplification of climate change) on frequency changes in European temperature extremes were addressed by Riebold et al. (2023).

2.2 Links between atmospheric processes and impacts by advancing statistical methods

One part of the *ClimXtreme* research aims to assess at which level of certainty observed climate change has caused a change in the probability and amplitudes of extreme weather events with near surface impacts, and for which spatio-temporal scales and dynamics of events. It is a topic of considerable interest to develop additional metrics for assessing changes in the spatio-temporal pattern of meteorological extremes. As mentioned above, *ClimXtreme* concentrates on the WCRP identified prototypical meteorological extreme events relevant in Europe mentioned above, on the relationships between their physical expressions, and on their impacts on certain socio-economic systems.

Besides basic developments, the application of statistics concentrated on climate change detection and attribution (D&A). Here one follows the classical D&A way according to the IPCC view. It is evaluated if the long term observations of most

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extreme events (i.e. events related to costly damages or impacts respectively) do show changes beyond their natural variability (detection) or can be classified as driven by external anthropogenic and/or non-anthropogenic forcing (attribution) both in a statistically significant way. This two-way view of the past is important to assess the causal necessity of specific external driving forces such as anthropogenic greenhouse gas emission for the observed changes following Pearl (2009).

To assess the future influence of anthropogenic induced climate change on extreme meteorological events with respect to their rareness, severity and impacts an ensemble of model projections at highly resolved regional scales has been analyzed. This was the basis to find out if the upcoming anthropogenic induced climate change modifies extreme weather events in the future with respect to their dynamics, intensity, frequency, location and spatio-temporal characteristics. In contrast to the look into the past, this analysis evaluates whether future anthropogenic greenhouse gas emissions will be sufficient causes of future extreme events (Pearl, 2009).

2.3 Linking hazards to impacts

Atmospheric extremes are not necessarily associated with (adverse) impacts on society, infrastructure or to the natural environment. The occurrence of such effects ("damage") depends on the existence of items or structures that can be damaged ("exposure"), and the possibility that they are affected by a hazard ("vulnerability" or "sensitivity"). A hazard in this definition is the phenomenon that causes the damage, in combination with the exposure and vulnerability. There are close links between many kinds of meteorological extremes and damages, thus turning the extremes into hazards. The consideration of hazardous events as an additional approach in *ClimXtreme* adds important additional aspects: First, there is a clear societal or nature-related relevance of hazard occurrence, and thus with respect to changes potentially induced by increasing greenhouse gas concentrations. Second, if impact data are available, they can be used to confront the meteorological data with formally independent information. Third, this leads to a more complex view on hazards and extremes: the relationship of impacts and the occurrence of extremes is often non-linear, which can turn comparatively small changes in the meteorological extremes into major changes in terms of impacts and relevance. The approach also opens the view on hazards imposed by situations in which the combination or sequence of meteorological parameters produces damage while none of them is formally extreme (compound events). In a similar sense, sequences of meteorological states can be of relevance for an impact mainly associated with a particular extreme event, as they affect preconditions or vulnerability. With sufficient impact data, such influences can be estimated, as well as the nonlinearities between the meteorological parameters and the impacts. In the insurance and reinsurance context the joint actions of hazards, exposure and vulnerability are combined into probabilistic risk models. These models introduce large and modeled event sets to estimate the probability and severity of potential losses in case that rare hazards strike areas of high exposure with varying vulnerabilities. The impact related part of the *ClimXtreme* research aims at contributing to those risk modeling strategies.

2.4 Statistical attribution of single extreme events to climate change

A special cross-cutting task in *ClimXtreme* is the attribution of extremes to climate change, which integrates process understanding, the statistical evaluation and the impacts. The problem has also been identified in the WCRP Grand Science

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Challenge. The attribution of extreme events answers the question of how likely it is that human action is responsible for the occurrence of a particular extreme event in a probabilistic sense (Otto, 2023). This part of the attribution analysis of extreme atmospheric events needs an extra discussion rarely seen in the public, namely the massive difference between the analysis of past extremes, which have been observed despite their rareness, and the analysis of future extremes which might happen despite their rareness. In economics and social sciences these distinctions are known as the *ex-post* and *ex-ante* views. In Pearl (2009) it is shown that in the *ex-post* case the causal necessity of a certain driver (in our case anthropogenic climate change by increased greenhouse gases levels or varying aerosol conditions) can be evaluated. This is through the analysis of a so called factual scenario (a model of the past world as it was) versus a counterfactual one (looking at a past world without anthropogenic climate change drivers). For the *ex-ante* case of future extremes under climate change, the causal sufficiency of the climatic drivers needs to be addressed and assessed in a similar way with the help of scenario simulations by climate models. If causal sufficiency can be proven, it will be a profound affirmation for mitigation and adaptation measures.

An additional problem in attribution of regional (or synoptic scale) or local (e.g. sub-synoptic to convective scales) meteorological extremes is the intertwining or the interaction of the atmospheric thermodynamic and dynamic processes. In causal inference – let it be *ex-post* or *ex-ante* – this leads to the notion of identifying mediators and moderators (VanderWeele, 2015). The former are dynamic processes themselves influenced by the climate change drivers and lead to further changes in addition to the driver's direct effects on the regional/local extreme values. The latter are atmospheric processes which overlay the meteorological extremes without being influenced by the driving climate change. This might lead to either constructive or destructive interference with the direct or mediated causal influences of climate change on meteorological extremes. Therefore joint causal necessity and sufficiency of climate change and the distinction of mediators and moderators acting during extreme events can only be achieved by jointly looking at the past and the future through the combined use of complex climate models and observations. This directly connects to the second strain of attribution research, the storyline method as outlined e.g. by Shepherd et al. (2018). Both the probabilistic and the storyline approaches raised the importance of properly coordinated simulation, analysis and evaluation of extremes from (multi-) model output, which is essential to assess current states and to project future states and their changes relative to the current state.

2.5 Building Knowledge and Data Bases

The multiple interactions within the atmospheric system being relevant for the research objectives of *ClimXtreme* required additional work towards a firm foundation for a common observational and modeling data and software base which all participating parties used jointly to rely on identical inputs and exchange results among the sub- projects. Analyzing the dynamics of atmospheric – ocean – land surface processes related to high impact weather and derived from reanalyses and climate models in several sub-projects allows drawing conclusions both about the changing frequencies of the extremes, and their physically admissible amplitudes and space-time structures.

As outlined above a major issue is a lack of understanding of the physical mechanisms connecting the free atmosphere dynamics to high impact events at the surface and determining their significance in terms of impacts. The necessary coordinated simulation, analysis and evaluation of extremes from (multi-) model output was accomplished in *ClimXtreme* by deploying

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and maintaining the common data search and analysis platform *ClimXtreme* Central Evaluation System (XCES) at the German Climate Computing Center DKRZ. It is based on the Free Evaluation System (Freva), originally developed by the BMBF funded project MiKliP (Kadow et al., 2021). To ensure the sustainable use and exchange of digital data and software the XCES platform was implemented as a Freva instance and is available at https://www.xces.dkrz.de/. XCES jointly serves as a data search and an analysis platform, providing access to a wide range of modeling data, observational datasets, custom analysis tools created within the sub-projects (plugins), and history of analysis runs.

Additionally a specific knowledge base was established as the *ClimXtreme* event catalog (Buschow et al., 2026) organized as a project wide editable wiki page. The *ClimXtreme* event catalog concentrated on the WCRP prototypical meteorological extremes for mid latitudes in Europe. The catalog is set up for two sub-periods 1979-recent (satellite era) and 1939-1978 (pre-satellite era; for heavy precipitation the period 1880-1938 was considered as well), with a geographical distinction between Germany and the neighboring areas in Europe. The *ClimXtreme* catalog was compiled from corresponding records of the Germany's national meteorological service DWD and the Center for Disaster Management CEDIM at the Karlsruhe Institute of Technology KIT as well as from grey literature in the library of the Meteorological Section of the Institute of Geosciences, University of Bonn and internal *ClimXtreme* contributions from various sub-projects. The sources are part of the wiki document. It has been converted into an analyzable table to allow for a rough overview statistics available for download at Buschow et al. (2026). Fig.(2) shows a summary of the contents of the catalog (as of Dec. 2023). A total of 416 events are recorded, which are roughly equally distributed across the sub-events of heavy precipitation, wind storms and heatwaves & droughts (Fig.(2), pie chart bottom right). The time series on the top shows a supposed sharp increase since about the year 2000, but this is due to work on the catalog from the *ClimXtreme* network, which is preferably based on work related to the reanalysis data of the last two decades. The figure on the bottom left shows the seasonal course of the catalog events with a maximum due to heavy precipitation and heatwaves/drought events during the boreal summer months May till August, while wind storm events peak during the boreal winter December till March. An interesting, future task would be the comparison to other also international data bases and the merging of those bases into a common European and publicly available catalog of past extreme meteorological events.

This preliminary overview of past hazardous meteorological events underpins the classification proposed by the WCRP and the internal structure of research in *ClimXtreme*. Between 2021 and 2023, groups of specific *ClimXtreme* sub-projects were formed to address identified problems related to the prototypical extreme events. This process culminated in a series of publications that are now available as a special issue of an Copernicus Inter-Journal in NHESS/ASCMO/WCD. This joint work of the sub-projects in *ClimXtreme* and the need to communicate the scientific results to interested stakeholders have led to the establishment of the Hazard Specific Stakeholder Interaction Groups (HaSSI groups) in the current *ClimXtreme* Phase II. These groups are now taking the opportunity to summarize the individual publications of the special issue in order to create added value that demonstrates the importance and synergy of joint and trans-disciplinary work on anthropogenic climate change and changes in weather and climate extremes.

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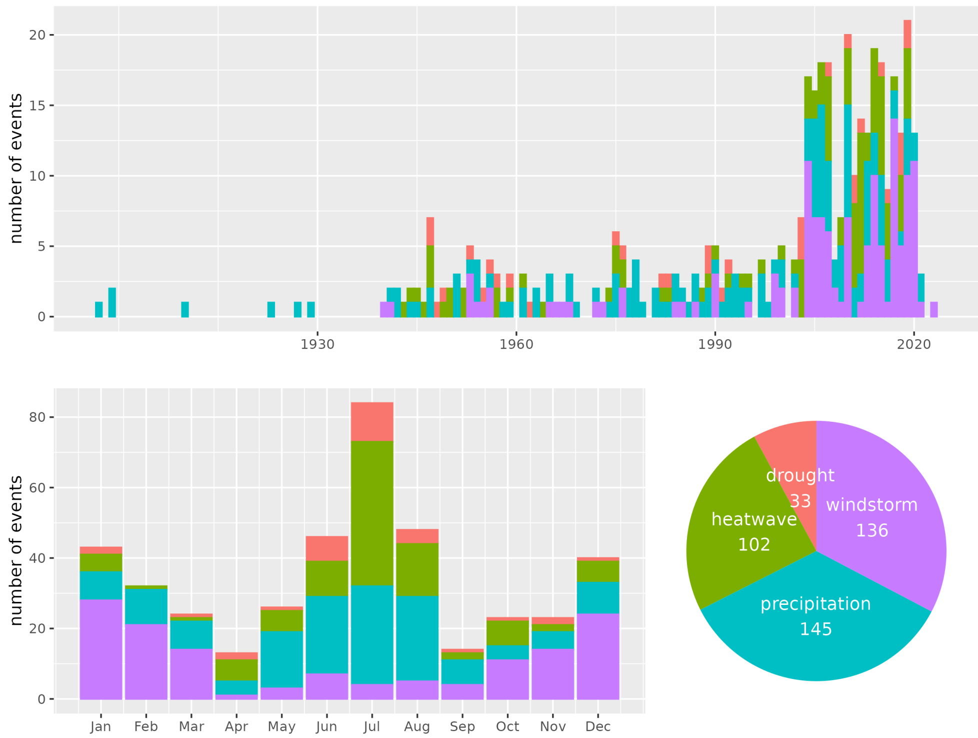

Figure 2. Summary statistics of the *ClimXtreme* event catalog on the four prototypical meteorological extreme events in Germany and its neighboring countries, labels inside the pie chart indicate the type of extreme events: droughts in brown, heatwaves in green, heavy precipitation in blue and wind storms in purple. Note that the figure reflects the data available in the catalog, not the statistics of events that really happened, for details see text

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2.6 Statements regarding recent extreme events

During the project's first phase, namely in 2021 and 2022, the occurrence of two extreme events in Mid Europe with Germany in the center put the general climate change D&A as well as the single event attribution into the center of public awareness:

– The catastrophic heavy precipitation event in the catchments of the rivers Ruhr, Wupper, Ahr, Erft, Rur and Maas/Meuse on 14th and 15th of July 2021 with more than 200 fatalities in Europe (ClimXtreme, 2021).

– the series of heavy wind storms of February 2022 (ClimXtreme, 2022).

These events were used as test beds for various joint analyses from the *ClimXtreme* sub-projects. These included the description and deeper analysis of the coupling between the three-dimensional atmospheric flows and their characteristics, the evaluation of indices outlining the events with respect to past observations, especially the past extremes, and the assessment

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of the impact of the meteorological extremes in the 2021/22 cases rainfall and wind. The results of that joint work have been summarized in the two statements available via the *ClimXtreme* web page ClimXtreme (2024). Such a timely response to hazardous events enabled sub-projects from *ClimXtreme* to contribute to the World Weather Attribution (WWA) study about the assessment of the heavy precipitation event in July 2021 in Tradowsky et al. (2023) following the protocol in Philip et al. (2020) and summarized in Otto (2023). Two further statements about more recent events in 2023 (the Christmas flooding in Northern Germany) and 2024 (the late spring flooding in Southern Germany) are presented on the webpage ClimXtreme (2024).

3 Hazard-specific research highlights

Although the individual sub-projects within the *ClimXtreme* program generally followed the overall research approach (see Section 2), they had different foci regarding the hazard types, their newly developed and applied methodologies, and their observational and modeling data bases. In total, 54 research plus two data publication have been produced. Twenty one publications enter the current special issue with the remaining 33 plus the data publication contributed to the overall research goals of *ClimXtreme* by other international and peer reviewed journals. The two central research questions stated in Sect. 1.1 are covered by a series of multi-author, cross-project and -disciplinary articles in this special issue (SI). They cover the archetypic heatwaves & droughts, heavy precipitation & floods and extreme wind storms. Each overview article is supported by a series of detailed studies on the respective extreme either with emphasis on observations or on methods. Additionally, accentuation is on the compound events and the question of the anthropogenically induced contributions to observed extremes: the ex-post climate change attribution problem. The following subsections of text provide a comprehensive summary of all peer reviewed *ClimXtreme* publications from the first phase.

- **Heatwaves & Droughts** Rousi et al. (2023) provided the pivotal review article on heatwaves and droughts using summer 2018 as a case study. Detailed studies on the spatio-temporal structure of European heatwaves can be found in Petrovic et al. (2024), in Szemkus and Friederichs (2024), or in Müller et al. (2020) and with respect to the comparison between past and future in Schielicke and Pfahl (2022). Further methods detecting and assessing the spatio-temporal structure of temperature extremes have been developed and tested in Buschow et al. (2024) and Schädler and Breil (2021). The characteristics of modeled droughts, particularly with respect to the model resolution, has been studied by Suarez-Gutierrez et al. (2023) and Suarez-Gutierrez et al. (2021) for global climate models simulating both the past and future. The representation and projections of heatwaves in regional climate models were analyzed by Hundhausen et al. (2023), while Petrovic et al. (2022) concentrated on droughts. The important question of drivers of mid-European heatwaves and droughts is studied in Schwitalla et al. (2020) and Xoplaki et al. (2025), with soil moisture as the candidate driver, while Beobide-Arsuaga et al. (2023) identify features of Atlantic sea surface temperature as relevant for heatwaves, and Riebold et al. (2023) discuss the link to high latitude sea ice changes. The impact of heatwaves and droughts on forest systems is discussed in a trans-disciplinary article by Knutzen et al. (2025), while Karwat and Franzke (2021) analyzed the impact of heatwaves on human life.

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- **Heavy Precipitation** The central cross-disciplinary *ClimXtreme* results on large and medium regional scales for heavy precipitation are being described in the overview articles by Mohr et al. (2023) and Ludwig et al. (2023), which focus on the July 2021 heavy precipitation and flooding event in western Europe. Details of that heavy precipitation have further been analyzed and quantified in Lengfeld et al. (2023). The general structure of such very heavy precipitation events is examined in Ruff and Pfahl (2023). The question of various large-scale forcings of heavy precipitation events is discussed with respect to the past in Capua et al. (2021), Mohr et al. (2020), and Hu and Franzke (2020). Hydrological changes under present and/or future climate conditions are presented in Ehmele et al. (2020), Ehmele et al. (2022), and Meredith et al. (2021). Local and smaller scale regional heavy precipitation are subject of analysis in Caldas-Alvarez et al. (2022) in an Eulerian and Meredith et al. (2023) in a Lagrangian approach. Hundhausen et al. (2024) analyzed changes of return levels of heavy precipitation for different time durations in regional climate model simulations. The *ClimXtreme* initiated description and analysis of heavy precipitation in space and time has seen a variety of innovative statistical approaches implemented during the course of the sub-project, ranging from quality control in El Hachem et al. (2022), through the detection of strong events by machine learning method in Bürger and Heistermann (2023), the derivation of specialized indices like Voit and Heistermann (2022) and Szemkus and Friederichs (2024) to advanced methods for estimation of statistical characteristic of heavy precipitation in Fauer and Rust (2023), Fauer et al. (2021), Bücher and Zanger (2023), and Lilienthal et al. (2022). Risk assessment for flooding in major river catchments in Germany following heavy precipitation events is an important impact measure, as discussed in Sairam et al. (2021). In this respect, rockfall events in the past and under future conditions are discussed in Nissen et al. (2022) and Nissen et al. (2023).

- **Wind storms** The review article Gliksman et al. (2023) focuses on mid-latitude wind storms and their impacts for various economic/societal sections, while detailed studies on the future occurrence of mid-latitude wind extremes were performed by Dolores-Tesillos et al. (2022) and Dolores-Tesillos and Pfahl (2024), targeting the Eulerian and Lagrangian perspectives. Based on idealized ICON simulations, Chen et al. (2024) analyzed the changes of the deepening mechanisms for cyclones, particularly diabatic processes. The observational perspective based on ERA5 data as well as in climate simulations can be found in Karwat et al. (2022) and Karwat et al. (2024), the latter focusing on cyclone clustering. The special properties of wind extremes and their effects on surges in the North Sea have been studied by Mayer et al. (2022a) using the data set described in Mayer et al. (2022b). An important statistical-mathematical contribution to describe and study the often observed series of wind storms is from Mathieu et al. (2025). Gardiner et al. (2024) and Lorenz et al. (2025) test and apply wind damage models to predict the impact of wind and storms on trees along railway infrastructure. Finally, Xoplaki et al. (2025) looked into the compound impact of precipitation and wind characteristics of wind storms.

- **Attribution** As outlined in Sect. 2.4 an important point of research on weather and climate extremes is the causality issue: the amount of human influences on an observed extreme. In *ClimXtreme*, such a study on the heavy precipitation events during July 2021 in the western part of Germany leading to severe flooding of the river catchments Ruhr, Ahr, Erft, Rur, Maas/Meuse has been undertaken in Tradowsky et al. (2023). An important input is reliable observations to

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assess the probabilistic properties in intensity and frequency of such rare events. This has been done using the innovative statistical approaches of Bücher and Zanger (2023) and Zanger et al. (2024). Attribution studies rely on the comparison of observations with simulations of the factual vs the counterfactual scenarios. To enhance the observational basis, stochastic weather generators can emulate the real observations of extreme weather events, as in Nguyen et al. (2021) and Ullrich et al. (2021)

In addition to this general overview of the publications from *ClimXtreme*, their interconnections and the individual subproject specific results, now the subsections below highlight some major advances to our current understanding of the connection between climate change and hazards occurrence in deeper details.

3.1 Heatwaves & Droughts

Heatwaves are extended periods of temperatures higher than a climatological threshold, while droughts are periods with precipitation sums lower than their long-term seasonal means. Both are relevant for many economic fields and often coupled. Being closely related to temperature rise, as the most direct consequence of greenhouse gas emissions, heatwaves/droughts are of primary concern when studying climate change and extreme weather events.

3.1.1 Overview of scientific developments

Reasoned by the quite different geographical conditions and types of impacts, there are various generally accepted ways to define heatwave and related indices. Table 1 provides an overview of indices for heatwaves and droughts applied in *ClimXtreme* studies. For heatwaves, common metrics include the number of events, heatwave days, and mean duration. Several indices capture intensity: the cumulative heat (CumHeat; Katavoutas and Founda, 2019) and the heatwave magnitude index (HWMId; Russo et al., 2014) both combine duration and intensity of T_{max} exceedances. The extremal pattern index (EPI; Szemkus and Friederichs, 2024) quantifies spatial patterns of strongly pronounced T_{max} and therefore differs from grid-point-based definitions by incorporating spatial information through measures of spatial dependence. The universal thermal climate index (UTCI; Jendritzky et al., 2007) takes a health-oriented perspective by integrating several meteorological variables relevant to human health and well-being.

Most studies of drought within *ClimXtreme* rely on the standardized precipitation evaporation index (SPEI; (Vicente-Serrano et al., 2010)), typically on 3–6 month scales, with PET derived via the modified Hargreaves equation. Drought is often defined at SPEI ≤ -1 (McKee et al., 1993). Similar to heatwave metrics, the number of drought events per year and their mean duration are also considered to assess changes in frequency and persistence.

Xoplaki et al. (2025) consider drought events from various perspectives, including different drought types and compound characteristics, thereby providing a comprehensive view on the exceptionally hot and dry conditions over Europe in 2018. Among other variables, they use the compound stress indicator (CSI), which is defined by a combination of standardized HWMId and SPEI anomalies (Zampieri et al., 2017) and the threshold-based EPI (TEPI; Szemkus and Friederichs (2024)), which analyses patterns of joint extremes in two variables.

Despite the diverse perspectives, resulting from the applied indices, the results broadly confirm the IPCC findings (Seneviratne et al., 2021). Multiple studies show increasing frequency and intensity of heatwaves in Germany and Europe (Petrovic et al., 2024, 2022), as well as longer event durations (Hundhausen et al., 2023; Schielicke and Pfahl, 2022). Evidence for rising compound extremes of heat and drought has also been reported (Xoplaki et al., 2025; Suarez-Gutierrez et al., 2023).

Atmospheric circulation emerges as the dominant driver of heatwave development, as evidenced, by the strong influence of geopotential height in the middle troposphere (Buschow et al., 2024). In this context, the increasing persistence of double-jet structures contributes to accelerated heatwave trends, particularly in Western Europe (Rousi et al., 2022). Land–atmosphere coupling represents another key mechanism that influences both the occurrence and intensity of heat waves. In particular, soil moisture deficits can strongly limit evapotranspiration, thereby amplifying surface heating, although the relative importance of this process varies regionally and may shift northward under warmer and drier conditions Schwitalla et al. (2025). Finally, Beobide-Arsuaga et al. (2023) point to the influence of oceanic conditions: Specific sea surface temperature anomaly patterns in the North Atlantic can act as a source of Rossby waves and hence influence European heatwaves.

Table 1. Summary of investigated characteristics of heatwaves & Droughts

Heatwave Index	**References**
n days	Petrovic et al. (2024); Buschow et al. (2024); Schielicke and Pfahl (2022); Hundhausen et al. (2023)
n events	Petrovic et al. (2024); Buschow et al. (2024); Schielicke and Pfahl (2022)
mean duration	Petrovic et al. (2024); Schielicke and Pfahl (2022); Hundhausen et al. (2023)
CumHeat (Katavoutas and Founda, 2019)	Petrovic et al. (2024); Rousi et al. (2023, 2022); Suarez-Gutierrez et al. (2023); Beobide-Arsuaga et al. (2023)
(cumulated) UTCI (Jendritzky et al., 2007)	(Rousi et al. (2023)); Hundhausen et al. (2023)
HWMId (Russo et al., 2014)	Hundhausen et al. (2023); Schielicke and Pfahl (2022)
EPI (Szemkus and Friederichs, 2024)	Xoplaki et al. (2025); Szemkus and Friederichs (2024)
Drought Index	**References**
n events	Petrovic et al. (2022)
mean duration	Petrovic et al. (2022)
SPEI (Vicente-Serrano et al., 2010)	Petrovic et al. (2022); Rousi et al. (2023); Xoplaki et al. (2025); Knutzen et al. (2025)
EPI (Szemkus and Friederichs, 2024)	Xoplaki et al. (2025)
Compound Heatwave & Drought Index	**References**
CSI (see Zampieri et al., 2017)	Xoplaki et al. (2025)
TEPI (Szemkus and Friederichs, 2024)	Xoplaki et al. (2025)

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3.1.2 Joint studies within *ClimXtreme*: Compound heat & drought in Germany 2018

As part of a collaborative effort within the *ClimXtreme* research network, Rousi et al. (2023) and Xoplaki et al. (2025) conducted a case study on the extreme hot and dry conditions experienced in Europe during the summer of 2018. The aim of both studies was to pool knowledge within *ClimXtreme* and to provide a comprehensive description of the event. The summer of 2018 is considered as the most intense hot and dry period in German observational history (see Zscheischler and Fischer, 2020). Fig.(3) provides an overview of the heatwave pattern and associated drought conditions in 2018. The heatwave initially developed over Scandinavia in mid-July, then spread to central Europe and later to the Iberian Peninsula. Lasting for approximately four weeks, it was marked by severe drought conditions, especially in northern and central Europe.

Rousi et al. (2023) focus on the atmospheric dynamics and processes of the heatwave. A key finding points to the presence of a persistent double jet structure over Eurasia in July 2018, which likely facilitated the onset of the heatwave (see also Rousi et al., 2022). Xoplaki et al. (2025) support this finding, showing that the regions affected by the heatwave corresponded to areas with weak winds between the polar and subtropical jets. Rousi et al. (2023) further identify several mechanisms driving the heatwave, including a blocking high pressure system over Scandinavia being an alter-ego feature of the double jet structure. The heatwave peaks in August over the Iberian Peninsula were likely caused by atmospheric ridges, which are known to be primary drivers of heatwaves and droughts in this region (see Sousa et al., 2019; Woollings et al., 2011).

Xoplaki et al. (2025) focus on the compound nature of the hot and dry summer of 2018. They report an intense 90-day precipitation deficit that preceded the heatwave by several days, likely contributing to the extreme temperatures observed being in line with (Schwitalla et al., 2025). From early summer 2018, an abnormal soil moisture deficit is recorded, extending up to 2.89 m equivalent water level and resulting in severe agricultural and hydrological droughts. While the soil moisture in the upper layers recovered during the following winter (2018/2019), the deeper layers did not fully recover until Winter 2019/2020 due to ongoing drought conditions in summer 2019. Consequently, the combined drought and heatwave of 2018 had significant impacts on the agriculture and forestry, with crop yields in Germany estimated to be 13% below the average of the previous three years (Xoplaki et al., 2025). Knutzen et al. (2025) also analyze the 2018 heat and drought summer, but with a focus on European forests and legacy effects extending to 2022. The authors conclude that e.g., in Germany, about 5% of forest area was lost between 2018 and 2021 due to recurring summer droughts in 2019, 2020, and 2022, which caused physiological stress, insect infestations, and fires.

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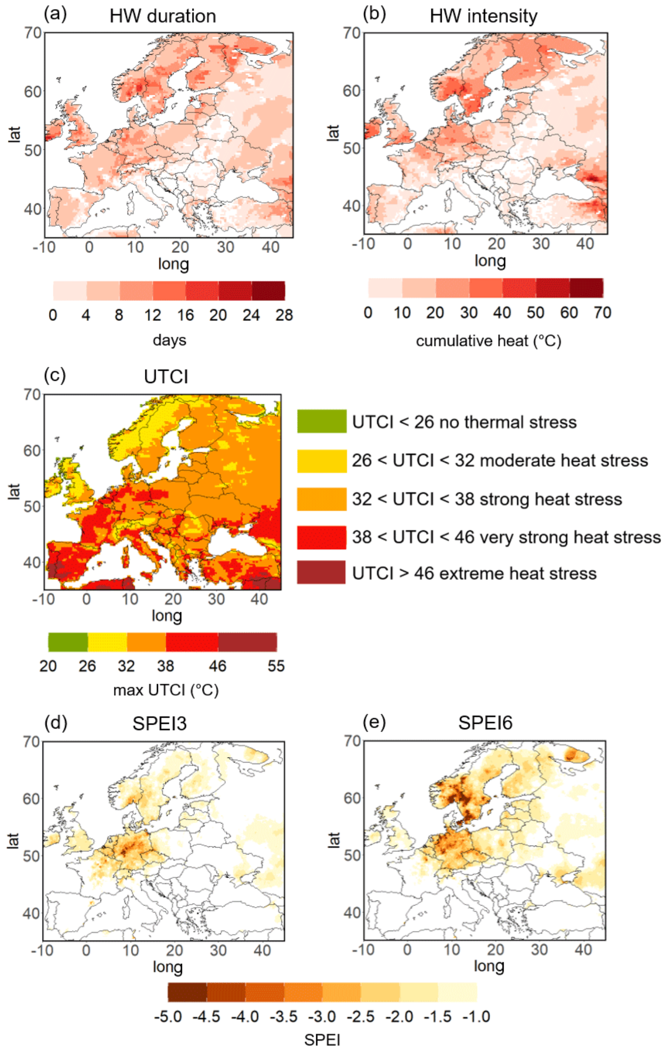

Figure 3. Indicators of the heatwave 2018 in Europe, measured by heatwave duration (a), heatwave intensity (b), the universal thermal climate index UTCI (c) and the standardized precipitation evaporation index SPEI calculated for a three month (d) and a 6 month (e) period. Details of the indicators are listed in Table 1, source: Rousi et al. (2023)

Summarizing Section (3.1)

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ClimXtreme publications highlight that Europe, particularly the Mediterranean and Central Europe, emerges as a heatwave hotspot, with frequency and magnitude having increased up to three to four times faster than in the Northern Hemisphere as a whole (Rousi et al., 2022; Suarez-Gutierrez et al., 2023; Buschow et al., 2024) with a physical explanation still pending.

ClimXtreme studies showcase how various processes, including atmospheric dynamics, land surface processes, and oceanic anomalies can interact to drive the formation and intensification of European heat waves.

ClimXtreme results highlight the summer of 2018 over Europe as an outstanding example of a complex weather extreme. The multi-faceted examination of this specific event using diverse methods elucidate the importance of atmospheric dynamics in their long-term impacts on ecosystems.

3.2 Heavy Precipitation

3.2.1 Indices for extremeness

The characteristic of heavy precipitation events can be very different on their spatial and temporal scales. However, almost none of the indices or measures of extremeness take into account the extremity across strongly varying spatial and temporal scales. Rather, only one spatial or temporal scale is chosen for a particular event, which makes comparison difficult. Voit and Heistermann (2022) in a novel approach complemented the weather extremity index (WEI) from Müller and Kaspar (2014) with a cross-scale WEI (xWEI), which integrates the cross-scale extremeness over relevant scales of heavy precipitation events. The new approach reveals that the most extreme events (e.g. the heavy precipitation events over western Germany in July 2021, those over Berlin in June 2017 or over Saxony in August 2002) are similarly captured by both indices. WEI events with less extremity but which actually caused significant socio-economic damages (e.g. heavy precipitation events over Baden-Wuerttemberg in May 2016 or over North Rhine-Westphalia in July 2014) due to compound inland floods (Thieken et al., 2022), are rated considerably more extreme from the xWEI.

Lengfeld et al. (2023) used these two indices for a reassessment of the heavy precipitation event in western Germany in July 2021. Due to a short time series, the necessary estimation of the parameters of a generalized extreme value distribution (GEV) has changed and the extreme event of July 2021 changes into the fourth most extreme event compared rank one in the analysis of Voit and Heistermann (2022) . This demonstrates the strong sensitivity of the indices to extreme value statistics when based on relatively short time series of 20 years or even shorter.

Another approach to derive a scale-independent heavy precipitation index is the Precipitation Severity Index (PSI, Caldas-Alvarez et al., 2023, 2022), which as well takes peak intensity, affected area and persistence into account, allowing for a direct comparison of the extremeness between different events or between different spatial resolutions of the underlying data sets.

3.2.2 Analysis of atmospheric extreme event conditions by case studies

Heavy precipitation regularly originates from combined effects with concurrent other natural hazards, creating compound events. As such events occurred in an exceptional sequence in 2018 over Europe, Xoplaki et al. (2025) investigated the in-

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terplay of the extreme events and their characteristics. In the winter of 2017/18, a series of severe storms accompanied by heavy precipitation from a warm front north and a cold front south of the cyclone centers caused extensive damage. During summer 2018 severe convective storms with high precipitation occurred on the western flank of an atmospheric blocking over Scandinavia for several days which caused the heat and drought conditions over Germany and central Europe discussed in section (3.1.2). This compound of regional or local extremes caused by a common atmospheric pattern is typical for blocking high pressure systems (Kautz et al., 2022; Mohr et al., 2020). Therefore, blocking highs are prime candidates acting as either a mediator or a moderator process (VanderWeele, 2015) of joint heavy precipitation at one place and concurrent heatwave events at another place, thereby not allowing these extreme events to be counted as independent. This also means that the persistent convective events steered by large-scale blocking, increase the risk of flooding for specific regions if e.g. relevant structures of orography are hit. These findings contribute to a better process understanding of compound heavy precipitation.

Rockfall as another hazardous weather and climate related impact was addressed by Nissen et al. (2022) for present day climate and by Nissen et al. (2023) for future climate scenarios using regional model output and a landslide database for Germany (Rupp and Damm, 2020). Precipitation amount and intensity on the day of the event is confirmed as the most important factor for the hazard under present day conditions, but freeze–thaw cycles and subsurface moisture during the preceding days also influence the probability by factors 2 to 4. These new detailed insights of specific factors contributing to extreme rockfall events are important for a better process understanding and therefore for predicting such events. With respect to the climate change signal, Nissen et al. (2023) estimate a reduction of event numbers of about 10% towards the end of a RCP8.5 period, mainly from a reduction of freeze-thaw-cycles in local winter. The authors also support this outcome from the numbers of weather patterns identified as relevant for rockfall, which are also reduced in the scenario. These results enable one to better assess the risk of rockfall in a warmer future climate and the factors that influence such events.

The heavy precipitation and flooding event over western Germany in July 2021 partly also originates from compound characteristics, in that multiple drivers overlaid and amplified each other. In a multi-disciplinary assessment of that event, Mohr et al. (2023) identified an upper tropospheric low-pressure system south of the Alps, ahead of an upper-level trough, propagating rather slowly due to a large and already long-lasting quasi-stationary anticyclone over northeastern Europe. They found that the atmosphere over central Europe contained extremely moist air masses that had been mainly fed by evaporation from northern central Europe as well as from the north and the Baltic Sea. Radar images showed that total precipitation was a compound of predominantly stratiform precipitation with embedded convective rain cells. This led to maximum daily precipitation rates of up to 150 mm, e.g. over the Cologne - Bonn area. Further compound characteristics came into play when looking also at hydrological and hydro-morphodynamic processes. The weeks before the event have seen frequent rainfall over the flood region (see also DWD, 2021), leading to a widespread wet period with an elevated soil moisture content. The July 2021 extreme flooding event was initiated and influenced by all these (and even more) different factors, resulting in one of the five heaviest precipitation - flooding events of the past 70 years in Germany. Ludwig et al. (2023) put this event into a historical and future context, finding that the flood peak levels are comparable to reconstructed major past events of 1804 and 1910 in the Altenahr - Ahrweiler region. That said, it is of high importance that these events and the interplay of various factors are fully understood in order to assess risks for future events and predict them at an early stage. Among other things, this event serves as a good

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example of how the ClimXtreme project enables a detailed and robust analysis to be carried out through the synergy between different working groups and sub projects. For an evaluation of the influence of climate change on the July 2021 event, Ludwig et al. (2023) implemented storyline guided simulations with a regional climate model.

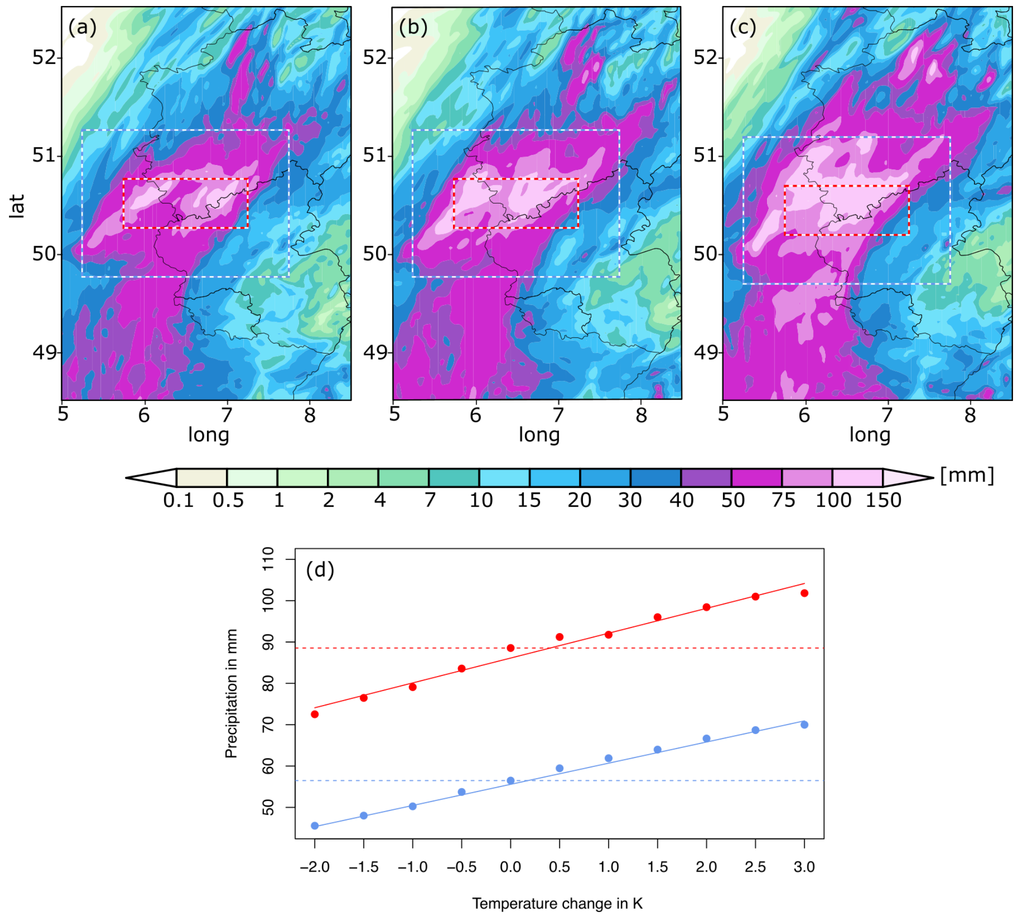

Figure 4. 24 h precipitation sums (14 July 2021, 06:00 UTC to 15 July 2021, 06:00 UTC) from PGW experiments using the WRF model. Horizontal distributions for (a) PGW -1 K, (b) control run ±0 K, and (c) PGW +2 K. (d) Area averaged 24 h precipitation sums (outer rectangle blue, inner in red) plotted against temperature change for all conducted PGW experiments. Solid lines represent linear regression lines that are used for calculating the correction factors for the hydrological discharge modeling. Stippled horizontal lines denote the mean 24 h precipitation amount of PGW control run (56.5 mm for the outer and 88.5mm for inner rectangle). Adapted from: Ludwig et al. (2023)

As shown in Fig.(4), the event was re-simulated for different levels of global warming, altering the mean temperature state (-2 K to +3 K). An increase in global temperature by 2 K leads to a precipitation increase of 11-18%, depending on the selected area. The response of a hydrological model driven by the results of the climate model reveals a 39% increase in the flood peak for an 18% increase in rainfall, highlighting that hydrological responses to meteorological drivers may potentially magnify the hazard in a warmer climate.

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Similar benefits of a multi-disciplinary assessment of a historical heavy precipitation event are also illustrated in Caldas-Alvarez et al. (2022) for the June 2017 heavy precipitation event over the Berlin metropolitan area. The extreme event was associated with two shortwave surface cyclones over the British Isles and Poland, downstream of a quasi-stationary upper-level trough over western Europe. A southwesterly advection of warm and moist air masses in combination with low-level wind convergence near Berlin induced over 11,000 convective cells, resulting in heavy precipitation amounts of up to 196 mm in 24 hours and in it being the costliest event between 2002 and 2017 in the Berlin metropolitan area. Attribution experiments along the storyline method showed that the highest precipitation rates are intensified by 10% by the thermodynamic climate change signal and that changes in anthropogenic aerosol emissions might increase the probability of heavy precipitation rates even more. In summary, they were again able to identify important meteorological processes, to relate them to statistical approaches for multi-scale return periods and to connect them to impacts on socio-economic factors as well as to show that a detailed evaluation of historical extreme events is indeed beneficial for future safety structures. The results again indicate the importance of compound effects of flow dynamics and thermodynamics in generating heavy precipitation events. The mediator effects of atmospheric dynamics on the direct thermodynamic changes by anthropogenic climate change and the moderator effects of unforced atmospheric variability are important for future risk management and event attribution studies of past heavy precipitation.

In terms of daily precipitation totals, the July 2021 and June 2017 events were larger than a 100-year return level event (Ludwig et al., 2023; Caldas-Alvarez et al., 2022). In order to analyze general circulation features of very heavy precipitation events, Ruff and Pfahl (2023) robustly investigated typical atmospheric processes of 100-year return level precipitation events over the central European river catchments. Such extreme events are often associated with an upper-level cut-off low and a surface cyclone southeast of that upper level low in combination with advection of moist air masses from central and eastern Europe. This pattern is associated with many historical events including in parts the June 2017 event over Berlin (Caldas-Alvarez et al., 2022). They also often feature an upper-tropospheric potential vorticity (PV) anomaly and develop from Rossby wave breaking. These findings contribute to a robust and better understanding of such very heavy precipitation events, which will probably become more frequent in a warmer climate. They do provide physical insights into the underlying processes e.g. through the analysis of the PV anomaly which can indicate not only the strength of anomalies of the horizontal flow and vertical stability but also the related spatial scales (Hoskins et al., 1985).

3.2.3 Improvements for heavy precipitation model simulations

The historical heavy precipitation events and their related compound events often resulted in devastating impacts on the socio-economic system. A better risk assessment and event forecast is necessary for reducing these impacts. Although there are already high-resolution models which allow the explicit representation of deep convective processes as drivers of heavy precipitation, it is not clear how the currently possible resolution affects the actual representation of heavy precipitation in the models. Caldas-Alvarez et al. (2023) evaluated this representation for heavy precipitation over the greater Alpine region for convection-permitting simulations. They showed that convection-permitting models (CPM) generate better rank correlations,

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better hit rates for extreme event detection and an improved representation of heavy precipitation amounts and its structure when compared to actual point wise observations.

Bürger and Heistermann (2023) evaluated the use of classical statistics and deep learning methods for conditions of deep convection with respect to the occurrence of heavy precipitation over Germany. Overall, they did not find substantial benefits of the deep learning methods over the conventional ones. Simulations of a future atmosphere also reveal that the probability of convective conditions on summer days will increase by about 10-20%. This point underlines once more the importance to consider the embedding large scale atmospheric flow when studying extremes with the aim of risk assessments and management in the future or for tackling the task of single event attribution in observations.

Summarizing Section (3.2):

ClimXtreme entered new ground by developing indices of heavy precipitation comprising information about potential impacts and information about the maximum extent and most extreme duration of such events. A more overarching evaluation of heavy precipitation is now possible.

ClimXtreme advanced the atmospheric and oceanic mediator and moderator concept needed for both the risk management and the event attribution. The use of multiple drivers separated in processes is applied in case studies of compound heavy precipitation. This method enables improved event attribution studies (to climate change) which require the joint evaluation of the local precipitation amounts with the structure of the driving atmospheric flow.

The *ClimXtreme* case studies of June 2017 and July 2021 identify previously underestimated importance of upper level cut-off lows and the associated potential vorticity anomalies as drivers of heavy precipitation. These meteorological processes are also statistically analyzed for multi-scale return periods and connected to socio-economic impacts. Detailed evaluation of historical extreme *(ex-post)* events prove their benefit for future safety structures. The results also indicate the importance of compound effects of flow dynamics and thermodynamics in generating heavy precipitation events, stressing the mediator effects of atmospheric dynamics on the direct thermodynamic changes by anthropogenic climate change and the moderator effects of unforced atmospheric variability.

ClimXtreme studies prove the benefits of Convection Permitting Models (CPM) for heavy precipitation simulations. These models are indispensably needed in providing realistic rainfall information for future risk management.

3.3 Extratropical Cyclones and Wind storms

Extreme wind speeds pose threats to various socio-economic sectors, such as infrastructure, forests, agriculture, transport, and energy (Gliksman et al., 2023). Among the events that are connected to extreme wind speeds, wind storms caused by intense extra tropical cyclones are the most damaging and represent the most costly natural hazard in Central Europe (Ulbrich et al., 2013). There is some consensus on certain trends, such as the zonal and annual averaged poleward shift of storm tracks, a decrease in total storm numbers and a tendency towards intensification of the most extreme extra tropical cyclones. However, cyclone activity undergoes strong natural variability which makes it difficult to identify clear trends. Additionally, competing mechanisms (e.g. polar amplification and increased latent heating) have an impact on changes in cyclone frequency and intensity (Ulbrich et al., 2009; Feser et al., 2014; Catto et al., 2019). Therefore, it is still uncertain if there is a significant

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change (ex-post) in observed wind storm frequency, intensity and impacts over the European mainland area (Feser et al., 2014; Pinto et al., 2023). The future risks (the ex-ante view) posed by extreme winds are complicated by uncertainties not only regarding storm trends but also in the interaction of storms with other meteorological and non-meteorological factors (Xoplaki et al., 2025; Lorenz et al., 2025). It underlines once more the necessity to distinguish between mediator and moderator processes as well as the exposure and vulnerability issues from the risk modeling.

Large-scale wind storms in the mid-latitudes are linked to intense cyclones or to a secondary cyclone in the trailing front of a steering (primary) cyclone (Priestley et al., 2020). The cyclone growth is related to baroclinicity, and thus to the thermodynamic characteristics (temperature gradients) of the large scale mean flow, and to diabatic processes like latent heat release (Wernli and Gray, 2024). On the local scale, extreme wind gusts can be related to convection, either as organized mesoscale systems or to the frontal dynamics of mid-latitude cyclones.

Dolores-Tesillos et al. (2022) investigated intensity and structural changes in extra tropical cyclones associated with a warmer climate by analyzing cyclone composites derived from Community Earth System Model Large Ensemble (CESM-LE) simulations. While only minor changes in cyclone intensity were found, the authors identified a spatial redistribution of low-level wind maxima. In particular, they found an extended wind footprint along intensified wind speeds in the warm sector south-east of the cyclone center. These changes were driven by changes in potential vorticity (PV) anomalies on different vertical levels. For lower-tropospheric levels they found an amplified PV anomaly near the cyclone center connected to enhanced diabatic heating. For upper-tropospheric levels they found a projected PV increase near the cyclone center and a decrease to the south and southwest. To investigate the reasons for theses PV changes they then studied the CESM-LE simulations from a Lagrangian perspective (Dolores-Tesillos and Pfahl, 2024). Their results indicate the interaction of dynamic and thermodynamic processes. They showed that the low-level PV changes in a warmer climate are caused by increased moisture and stronger ascent in the warm conveyor belt which lead to more latent heat release. In contrast, upper-level PV changes are driven by a mix of factors, including cloud diabatic PV changes and anomalous PV advection.

Xoplaki et al. (2025) examined various types of compound events through a series of case studies focusing on Germany's exceptional year of 2018, marked by multiple multivariate extremes. The results and conclusions related to heat, drought and heavy precipitation have been summarized in Sect. 3.1.2and 3.2.2. With respect to wind-related events compounded with heavy precipitation Xoplaki et al. (2025) explored the connection between such compound events and economic losses. The impact on the German building sector from either single extreme wind events versus compound events involving both extreme wind and heavy precipitation was studied. Daily residential building loss data from the German Insurance Association (GDV) were split into days with and without compound events. Xoplaki et al. (2025) found distinctly higher losses associated with wind-precipitation-compound events. They evaluated projected changes in the frequency of compound events for recent (1975–2025) to near-term (2025–2075) future climate conditions based on the 30-member simulation of the global climate model CMIP6 MPI-GE.

Gliksman et al. (2023) provide a comprehensive review focused on the impacts of wind and storms and the meteorological processes that drive wind damages. They present an overview of the methods used to asses impacts such as storm intensity scales and storm severity indices. Their review covers various sectors affected by wind - forestry, urban areas and buildings,

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transport, agriculture, energy, and warning systems - describing the role wind and storms play in each, see Fig. (5). They thoroughly describe the different impact assessment methods used within these sectors. These methods include topographical and roughness indices, critical wind speed thresholds, wind power indices, and statistical loss models.

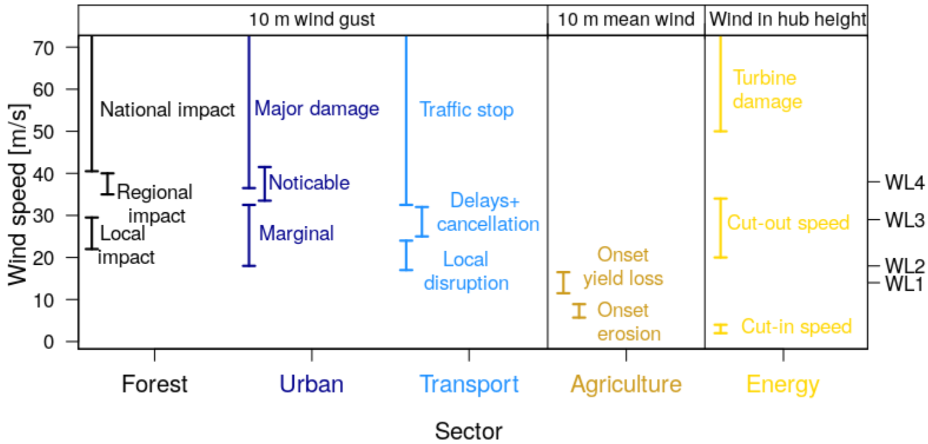

Figure 5. Critical thresholds of wind speed for five affected sectors. Source Gliksman et al. (2023)

Summarizing Section (3.3):

ClimXtreme studies of wind and storms have revealed the complex physical processes that cause windstorms of high damage potential. The timing and location of storms in their stage of maximum strength, in relation to the exposure of vulnerable assets, are decisive for the storm impact.

The *ClimXtreme* studies Dolores-Tesillos et al. (2022) and Dolores-Tesillos and Pfahl (2024) detected a process chain how a warmer climate might drive structural changes in cyclones.

The *ClimXtreme* study Xoplaki et al. (2025) based on the 30-member CMIP6 MPI-GE ensemble, found little change in the frequency of wind storm - heavy precipitation compound events but a distinct intensification of the associated wind speed maxima and heavy precipitation amounts.

The *ClimXtreme* review paper by Gliksman et al. (2023) serves as a comprehensive overview for anyone who wants to apply strategies to assess risk management for wind damage in different economic sectors.

4 Conclusions

The introductory notes and the detailed description of the *ClimXtreme* work on the archetypic meteorological extremes heat and drought, heavy precipitation and wind storms events in Germany / Central Europe has led to three important and overarching conclusions.

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- Partly based on classical univariate extreme value theory and partly extended by recent developments in multivariate extreme value statistics, indicators (or indices) to detect and monitor extreme events in space and time have been developed, applied to observations and simulations as guides for further analyses. The indices are strongly inspired by the local impacts of meteorological extremes. Therefore they concentrate on heatwaves and drought as well as heavy precipitation because especially the station data base of daily or sub-daily observations of the first two types of extremes is much richer than for heavy wind storm events. The use of high resolution reanalyses could ease this discrepancy. The numerical analysis procedures to derive the indices are part of the *ClimXtreme* XCES system and available for future use also outside the *ClimXtreme* community.

- In the joint analysis of physical processes and their statistical properties it became apparent that the various dynamical and thermodynamic climate processes have to be distinguished and refined by the concept of mediators and moderators. The former are dynamic processes themselves influenced by the climate change drivers and lead to further changes in addition to the driver's direct effects on the regional/local extreme values. The latter are atmospheric, oceanic or hydrological processes which overlay the meteorological extremes but not being influenced by the driving climate change themselves and therefore often named as "climate noise". This can lead to either constructive or destructive interference in space or time with the variability induced by direct or mediated causal influences of climate change on meteorological extremes. There is a strong need for further research on the mediator or moderator concept in the context of climate change and extremes. This distinction is directly linked to the differentiation between necessity and sufficiency of anthropogenic climate change being responsible for past (necessity, ex-post) and future (sufficiency, ex-ante) changes in extremes. It is important in the communication of past and the anticipation of future extreme events.

- In practically all *ClimXtreme* studies the relevance of the embedding large scale (in space and time) atmospheric environment became very clear. This is another indicator for a strong need to include the large scale atmospheric environment into the research of identification of mediator or moderator processes. The relevance of the embedding and its assessment as mediator / moderator vs. the direct influence by anthropogenic climate forcing is important for studying extremes with the aim of risk assessments and management in the future and reducing uncertainties of the climate model projections. Also for tackling the task of single event attribution to evaluate the current influence of anthropogenic induced climate change on a single observed extreme event the embedding large scale atmospheric environment is important for both (probabilistic and storyline) types of event attribution studies. Finally understanding of the physical interaction of dynamical and thermodynamic atmospheric, oceanic and hydrological processes during extreme events is an inherent part of the embedding large scale atmospheric flow.

Code availability. The analysis tools (plugins) developed within the *ClimXtreme* community are integrated into Freva-XCES and made available for future external use. Their code base is publicly accessible at DKRZ's GitLab under https://gitlab.dkrz.de/bm1159/plugins4freva/

The Freva framework code base itself is hosted at https://github.com/freva-org and is released under the permissive BSD-3 license, which also applies to derived plugins unless stated otherwise by their developers.

Data availability. The data accessible via XCES is hosted on DKRZ's high-performance computing (HPC) filesystem. Most large modeling datasets (e.g., CMIP6, CMIP5, CORDEX) are provided through the DKRZ Data Pool (`/pool/data`). Reanalysis and observational datasets specific to *ClimXtreme* are maintained in a dedicated project directory at `/work/bm1159/XCES/data4xces`.

Author contributions. A-H, C-K, JG-P, U-U, F-K drafted the overview paper and wrote the first version of the introductory notes for the *ClimXtreme* program, P-F,S-B,S-S,J-G,H-F,D-N,R-L,F-R,EE-LE corrected, modified and added that part, S-S,S-B,P-F contributed the Heat-wave/drought section, H-F,JG-P, J-G, R-L, F-R contributed contributed the wind storm section and the heavy precipitation section, D-N, EE-LE provided all code, data store related parts, all authors reviewed and crosschecked the final version.

Competing interests. At least one of the (co-)authors is a member of the editorial board of Natural Hazards and Earth System Sciences.

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References

Beobide-Arsuaga, G., Düsterhus, A., Müller, W. A., Barnes, E. A., and Baehr, J.: Spring Regional Sea Surface Temperatures as a Precursor of European Summer Heatwaves, Geophysical Research Letters, 50, e2022GL100 727, https://doi.org/10.1029/2022GL100727, 2023.

Bevacqua, E., De Michele, C., Manning, C., Couasnon, A., Ribeiro, A. F. S., Ramos, A. M., Vignotto, E., Bastos, A., Blesić, S., Durante, F., Hillier, J., Oliveira, S. C., Pinto, J. G., Ragno, E., Rivoire, P., Saunders, K., van der Wiel, K., Wu, W., Zhang, T., and Zscheischler, J.: Guidelines for Studying Diverse Types of Compound Weather and Climate Events, Earth's Future, 9, e2021EF002 340, https://doi.org/https://doi.org/10.1029/2021EF002340, e2021EF002340 2021EF002340, 2021.

Bindoff, N. L., Stott, P. A., AchutaRao, K. M., Allen, M. R., Gillett, N., Gutzler, D., Hansingo, K., Hegerl, G., Hu, Y., Jain, S., et al.: Detection and Attribution of Climate Change: from Global to Regional, in: Climate Change 2013: the Physical Science Basis, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://hal.science/hal-03330685, 2014.

Bücher, A. and Zanger, L.: On the disjoint and sliding block maxima method for piecewise stationary time series, The Annals of Statistics, 51, 573–598, 2023.

Bürger, G. and Heistermann, M.: Shallow and deep learning of extreme rainfall events from convective atmospheres, Natural Hazards and Earth System Sciences, 23, 3065–3077, https://doi.org/10.5194/nhess-23-3065-2023, 2023.

Buschow, S., Keller, J., and Wahl, S.: Explaining heatwaves with machine learning, Quarterly Journal of the Royal Meteorological Society, 150, 1207–1221, 2024.

Buschow, S., Augenstein, M., Beobide-Arsuaga, G., Caldas-Alvarez, A., Feldmann, H., Kracheletz, M., Kunert, L., Kunz, M., Niermann, D., Pscheidt-Willems, I., Quinting, J., Richter, A., Schwitalla, T., Steidl, S., and Hense, A.: ClimXtreme Event Catalogue, https://bonndata.uni-bonn.de/previewurl.xhtml?token=b3808f3d-36fa-4cb7-9fb1-baf4452ed372, last accessed 08 May 2026, 2026.

Caldas-Alvarez, A., Augenstein, M., Ayzel, G., Barfus, K., Cherian, R., Dillenardt, L., Fauer, F., Feldmann, H., Heistermann, M., Karwat, A., Kaspar, F., Kreibich, H., Lucio-Eceiza, E. E., Meredith, E. P., Mohr, S., Niermann, D., Pfahl, S., Ruff, F., Rust, H. W., Schoppa, L., Schwitalla, T., Steidl, S., Thieken, A. H., Tradowsky, J. S., Wulfmeyer, V., and Quaas, J.: Meteorological, impact and climate perspectives of the 29 June 2017 heavy precipitation event in the Berlin metropolitan area, Natural Hazards and Earth System Sciences, 22, 3701–3724, https://doi.org/10.5194/nhess-22-3701-2022, 2022.

Caldas-Alvarez, A., Feldmann, H., Lucio-Eceiza, E., and Pinto, J. G.: Convection-parameterized and convection-permitting modelling of heavy precipitation in decadal simulations of the greater Alpine region with COSMO-CLM, Weather and Climate Dynamics, 4, 543–565, https://doi.org/10.5194/wcd-4-543-2023, 2023.

Capua, G. D., Sparrow, S., Kornhuber, K., Rousi, E., Osprey, S., Wallom, D., van den Hurk, B., and Coumou, D.: Drivers behind the summer 2010 wave train leading to Russian heatwave and Pakistan flooding, npj Climate and Atmospheric Science, 4, 55, https://doi.org/10.1038/s41612-021-00211-9, 2021.

Catto, J. L., Ackerley, D., Booth, J. F., et al.: The Future of Midlatitude Cyclones, Current Climate Change Reports, 5, 407–420, https://doi.org/10.1007/s40641-019-00149-4, 2019.

Chen, T.-C., Braun, C., Voigt, A., and Pinto, J. G.: Changes of Intense Extratropical Cyclone Deepening Mechanisms in a Warmer Climate in Idealized Simulations, Journal of Climate, 37, 4703 – 4722, https://doi.org/10.1175/JCLI-D-23-0605.1, 2024.

ClimXtreme, S. C.: Statement about the catastrophic rainfall event in July 2021, https://www.climxtreme.de/Post-AG_Event-Evaluation/phase-I_starkregen_assessment/index.html, accessed: September, 27th, 2025, 2021.

ClimXtreme, S. C.: Statement about the windstorm series during February 2022, https://www.climxtreme.de/Post-AG_Event-Evaluation/phase-I_sturm_assessment/index.html, accessed: September, 27th, 2025, 2022.

ClimXtreme, S. C.: The ClimXtreme Web page, https://www.climxtreme.de, accessed: September, 27th, 2025, 2024.

DKRZ, D. K. R.: Finding and Accessing Data, https://docs.dkrz.de/doc/dataservices/finding_and_accessing_data/index.html, last accessed 08 April 2026, 2026.

Dolores-Tesillos, E. and Pfahl, S.: Future changes in North Atlantic winter cyclones in CESM-LE – Part 2: A Lagrangian analysis, Weather and Climate Dynamics, 5, 163–179, https://doi.org/10.5194/wcd-5-163-2024, 2024.

Dolores-Tesillos, E., Teubler, F., and Pfahl, S.: Future changes in North Atlantic winter cyclones in CESM-LE – Part 1: Cyclone intensity, potential vorticity anomalies, and horizontal wind speed, Weather and Climate Dynamics, 3, 429–448, https://doi.org/10.5194/wcd-3-429-2022, 2022.

DWD: Hydro-klimatologische Einordnung der Stark-und Dauerniederschläge in Teilen Deutschlands im Zusammenhang mit dem Tiefdruckgebiet „Bernd “vom 12. bis 19. Juli 2021, Geschäftsbereich Klima und Umwelt, 2021.

Ehmele, F., Kautz, L.-A., Feldmann, H., and Pinto, J. G.: Long-term variance of heavy precipitation across central Europe using a large ensemble of regional climate model simulations, Earth System Dynamics, 11, 469–490, https://doi.org/10.5194/esd-11-469-2020, 2020.

Ehmele, F., Kautz, L.-A., Feldmann, H., He, Y., Kadlec, M., Kelemen, F. D., Lentink, H. S., Ludwig, P., Manful, D., and Pinto, J. G.: Adaptation and application of the large LAERTES-EU regional climate model ensemble for modeling hydrological extremes: a pilot study for the Rhine basin, Natural Hazards and Earth System Sciences, 22, 677–692, https://doi.org/10.5194/nhess-22-677-2022, 2022.

El Hachem, A., Seidel, J., Imbery, F., Junghänel, T., and Bárdossy, A.: Technical Note: Space–time statistical quality control of extreme precipitation observations, Hydrology and Earth System Sciences, 26, 6137–6146, https://doi.org/10.5194/hess-26-6137-2022, 2022.

Fauer, F. S. and Rust, H. W.: Non-stationary large-scale statistics of precipitation extremes in central Europe, Stochastic Environmental Research and Risk Assessment, 37, 4417–4429, https://doi.org/10.1007/s00477-023-02515-z, 2023.

Fauer, F. S., Ulrich, J., Jurado, O. E., and Rust, H. W.: Flexible and consistent quantile estimation for intensity–duration–frequency curves, Hydrology and Earth System Sciences, 25, 6479–6494, https://doi.org/10.5194/hess-25-6479-2021, 2021.

Feser, F., Barcikowska, M., Krueger, O., Schenk, F., Weisse, R., and Xia, L.: Storminess over the North Atlantic and northwestern Europe—A review, Quarterly Journal of the Royal Meteorological Society, 141, 350–382, https://doi.org/10.1002/qj.2364, 2014.

Gardiner, B., Lorenz, R., Hanewinkel, M., Schmitz, B., Bott, F., Szymczak, S., Frick, A., and Ulbrich, U.: Predicting the risk of tree fall onto railway lines, Forest Ecology and Management, 553, 121 614, https://doi.org/https://doi.org/10.1016/j.foreco.2023.121614, 2024.

Gliksman, D., Averbeck, P., Becker, N., Gardiner, B., Goldberg, V., Grieger, J., Handorf, D., Haustein, K., Karwat, A., Knutzen, F., Lentink, H. S., Lorenz, R., Niermann, D., Pinto, J. G., Queck, R., Ziemann, A., and Franzke, C. L. E.: Review article: A European perspective on wind and storm damage – from the meteorological background to index-based approaches to assess impacts, Natural Hazards and Earth System Sciences, 23, 2171–2201, https://doi.org/10.5194/nhess-23-2171-2023, 2023.

Hoskins, B. J., McIntyre, M. E., and Robertson, A. W.: On the use and significance of isentropic potential vorticity maps, Quarterly Journal of the Royal Meteorological Society, 111, 877–946, 1985.

Hu, G. and Franzke, C. L. E.: Evaluation of Daily Precipitation Extremes in Reanalysis and Gridded Observation-Based Data Sets Over Germany, Geophysical Research Letters, 47, e2020GL089 624, https://doi.org/https://doi.org/10.1029/2020GL089624, e2020GL089624 10.1029/2020GL089624, 2020.

Hundhausen, M., Feldmann, H., Laube, N., and Pinto, J. G.: Future heat extremes and impacts in a convection-permitting climate ensemble over Germany, Natural Hazards and Earth System Sciences, 23, 2873–2893, https://doi.org/10.5194/nhess-23-2873-2023, 2023.

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, International Journal of Climatology, 44, 1454–1471, https://doi.org/https://doi.org/10.1002/joc.8393, 2024.

Jendritzky, G., Havenith, G., Weihs, P., Batcharova, E., and DeDear, R.: The Universal Thermal Climate Index UTCI Goal and state of COST Action 730, Bioclimatology and natural hazards, 2007.

Kadow, C., Illing, S., Lucio-Eceiza, E. E., Bergemann, M., Ramadoss, M., Sommer, P. S., Kunst, O., Schartner, T., Pankatz, K., Grieger, J., et al.: Introduction to Freva–A free evaluation system framework for earth system modeling, Journal of Open Research Software, 9, 2021.

Karwat, A. and Franzke, C. L. E.: Future Projections of Heat Mortality Risk for Major European Cities, Weather, Climate, and Society, 13, 913 – 931, https://doi.org/10.1175/WCAS-D-20-0142.1, 2021.

Karwat, A., Franzke, C. L. E., and Blender, R.: Long-Term Trends of Northern Hemispheric Winter Cyclones in the Extended ERA5 Reanalysis, Journal of Geophysical Research: Atmospheres, 127, 1–19, https://doi.org/10.1029/2022jd036952, 2022.

Karwat, A., Franzke, C. L. E., Pinto, J. G., Lee, S.-S., and Blender, R.: Northern Hemisphere Extratropical Cyclone Clustering in ERA5 Reanalysis and the CESM2 Large Ensemble, Journal of Climate, 37, 1347–1365, https://doi.org/10.1175/jcli-d-23-0160.1, 2024.

Katavoutas, G. and Founda, D.: Response of Urban Heat Stress to Heat Waves in Athens (1960–2017), Atmosphere, 10, 483, https://doi.org/10.3390/atmos10090483, 2019.

Kautz, L.-A., Martius, O., Pfahl, S., Pinto, J. G., Ramos, A. M., Sousa, P. M., and Woollings, T.: Atmospheric blocking and weather extremes over the Euro-Atlantic sector–a review, Weather and climate dynamics, 3, 305–336, https://doi.org/10.5194/wcd-3-305-2022, 2022.

Knutzen, F., Averbeck, P., Barrasso, C., Bouwer, L. M., Gardiner, B., Grünzweig, J. M., Hänel, S., Haustein, K., Johannessen, M. R., Kollet, S., Müller, M. M., Pietikäinen, J.-P., Pietras-Couffignal, K., Pinto, J. G., Rechid, D., Rousi, E., Russo, A., Suarez-Gutierrez, L., Veit, S., Wendler, J., Xoplaki, E., and Gliksman, D.: Impacts on and damage to European forests from the 2018–2022 heat and drought events, Natural Hazards and Earth System Sciences, 25, 77–117, https://doi.org/10.5194/nhess-25-77-2025, 2025.

Köhler, P., Nehrbass-Ahles, C., Schmitt, J., Stocker, T. F., and Fischer, H.: A 156 kyr smoothed history of the atmospheric greenhouse gases CO_2, CH_4, and N_2O and their radiative forcing, Earth System Science Data, 9, 363–387, 2017.

Lengfeld, K., Voit, P., Kaspar, F., and Heistermann, M.: Brief communication: On the extremeness of the July 2021 precipitation event in western Germany, Natural Hazards and Earth System Sciences, 23, 1227–1232, https://doi.org/10.5194/nhess-23-1227-2023, 2023.

Lilienthal, J., Zanger, L., Bücher, A., and Fried, R.: A note on statistical tests for homogeneities in multivariate extreme value models for block maxima, Environmetrics, 33, e2746, https://doi.org/https://doi.org/10.1002/env.2746, 2022.

Lorenz, R., Becker, N., Gardiner, B., Ulbrich, U., Hanewinkel, M., and Schmitz, B.: Tree fall along railway lines: modelling the impact of wind and other meteorological factors, Natural Hazards and Earth System Sciences, 25, 2179–2196, https://doi.org/10.5194/nhess-25-2179-2025, 2025.

Lucarini, V., Faranda, D., Turchetti, G., and Vaienti, S.: Extreme value theory for singular measures, Chaos: An Interdisciplinary Journal of Nonlinear Science, 22, 2012.

Ludwig, P., Ehmele, F., Franca, M. J., Mohr, S., Caldas-Alvarez, A., Daniell, J. E., Ehret, U., Feldmann, H., Hundhausen, M., Knippertz, P., Küpfer, K., Kunz, M., Mühr, B., Pinto, J. G., Quinting, J., Schäfer, A. M., Seidel, F., and Wisotzky, C.: A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe – Part 2: Historical context and relation to climate change, Natural Hazards and Earth System Sciences, 23, 1287–1311, https://doi.org/10.5194/nhess-23-1287-2023, 2023.

Mathieu, C., Hees, K., and Fried, R.: Models for temporal clustering of extreme events with applications to mid-latitude winter cyclones, https://arxiv.org/abs/2308.14625, 2025.

Mayer, B., Mathis, M., Mikolajewicz, U., and Pohlmann, T.: RCP8.5-projected changes in German Bight storm surge characteristics from regionalized ensemble simulations for the end of the twenty-first century, Frontiers in Climate, Volume 4 - 2022, https://doi.org/10.3389/fclim.2022.992119, 2022a.

Mayer, B., Mathis, M., and Pohlmann, T.: Effects of climate change on extreme sea levels in the North Sea (ECCES): regionalized MPIOM-REMO climate ensemble, https://doi.org/10.26050/WDCC/ECCES_MPIOM-REMO, 2022b.

McKee, T. B., Doesken, N. J., Kleist, J., et al.: The relationship of drought frequency and duration to time scales, in: Proceedings of the 8th Conference on Applied Climatology, vol. 17, pp. 179–183, California, 1993.

Meredith, E. P., Ulbrich, U., Rust, H. W., and Truhetz, H.: Present and future diurnal hourly precipitation in 0.11 EURO-CORDEX models and at convection-permitting resolution, Environmental Research Communications, 3, 055 002, 2021.

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

Mohr, S., Wilhelm, J., Wandel, J., Kunz, M., Portmann, R., Punge, H. J., Schmidberger, M., Quinting, J. F., and Grams, C. M.: The role of large-scale dynamics in an exceptional sequence of severe thunderstorms in Europe May–June 2018, Weather and Climate Dynamics, 1, 325–348, https://doi.org/10.5194/wcd-1-325-2020, 2020.

Mohr, S., Ehret, U., Kunz, M., Ludwig, P., Caldas-Alvarez, A., Daniell, J. E., Ehmele, F., Feldmann, H., Franca, M. J., Gattke, C., Hundhausen, M., Knippertz, P., Küpfer, K., Mühr, B., Pinto, J. G., Quinting, J., Schäfer, A. M., Scheibel, M., Seidel, F., and Wisotzky, C.: A multi-disciplinary analysis of the exceptional flood event of July 2021 in central Europe – Part 1: Event description and analysis, Natural Hazards and Earth System Sciences, 23, 525–551, https://doi.org/10.5194/nhess-23-525-2023, 2023.

Müller, M. and Kaspar, M.: Event-adjusted evaluation of weather and climate extremes, Natural Hazards and Earth System Sciences, 14, 473–483, https://doi.org/10.5194/nhess-14-473-2014, 2014.

Müller, W., Borchert, L., and Ghosh, R.: Observed Subdecadal Variations of European Summer Temperatures, Geophysical Research Letters, 47, e2019GL086 043, https://doi.org/https://doi.org/10.1029/2019GL086043, e2019GL086043 2019GL086043, 2020.

Nguyen, V. D., Merz, B., Hundecha, Y., Haberlandt, U., and Vorogushyn, S.: Comprehensive evaluation of an improved large-scale multisite weather generator for Germany, International Journal of Climatology, 41, 4933–4956, https://doi.org/https://doi.org/10.1002/joc.7107, 2021.

Nissen, K. M., Rupp, S., Kreuzer, T. M., Guse, B., Damm, B., and Ulbrich, U.: Quantification of meteorological conditions for rockfall triggers in Germany, Natural Hazards and Earth System Sciences, 22, 2117–2130, https://doi.org/10.5194/nhess-22-2117-2022, 2022.

Nissen, K. M., Wilde, M., Kreuzer, T. M., Wohlers, A., Damm, B., and Ulbrich, U.: A decrease in rockfall probability under climate change conditions in Germany, Natural Hazards and Earth System Sciences, 23, 2737–2748, https://doi.org/10.5194/nhess-23-2737-2023, 2023.

Otto, F. E.: Attribution of extreme events to climate change, Annual Review of Environment and Resources, 48, 813–828, 2023.

Pearl, J.: Causality, Cambridge University Press, Cambridge New York, 2009.

Petrovic, D., Fersch, B., and Kunstmann, H.: Droughts in Germany: performance of regional climate models in reproducing observed characteristics, Natural Hazards and Earth System Sciences, 22, 3875–3895, https://doi.org/10.5194/nhess-22-3875-2022, 2022.

Petrovic, D., Fersch, B., and Kunstmann, H.: Heat wave characteristics: evaluation of regional climate model performances for Germany, Natural Hazards and Earth System Sciences, 24, 265–289, https://doi.org/10.5194/nhess-24-265-2024, 2024.

Philip, S., Kew, S., van Oldenborgh, G. J., Otto, F., Vautard, R., van der Wiel, K., King, A., Lott, F., Arrighi, J., Singh, R., and van Aalst, M.: A protocol for probabilistic extreme event attribution analyses, Advances in Statistical Climatology, Meteorology and Oceanography, 6, 177–203, https://doi.org/10.5194/ascmo-6-177-2020, 2020.

Pinto, J. G., Feser, F., Ludwig, P., and Reyers, M.: Der Klimawandel: Auswirkungen auf Winde und Zyklonen, in: Klimawandel in Deutschland. Entwicklung, Folgen, Risiken und Perspektiven, edited by Brasseur, G. P., Jacob, D., and Schuck-Zöller, S., pp. 85–94, Springer Spektrum, Berlin, Heidelberg, https://doi.org/10.1007/978-3-662-66696-8_8, 2023.

Priestley, M. D. K., Dacre, H. F., Shaffrey, L. C., Schemm, S., and Pinto, J. G.: The role of secondary cyclones and cyclone families for the North Atlantic storm track and clustering over western Europe, Quarterly Journal of the Royal Meteorological Society, 146, 1184–1205, https://doi.org/10.1002/qj.3733, 2020.

Prigogine, I. and Hiebert, E. N.: From being to becoming: Time and complexity in the physical sciences, American Institute of Physics Publishing, 1982.

Riebold, J., Richling, A., Ulbrich, U., Rust, H., Semmler, T., and Handorf, D.: On the linkage between future Arctic sea ice retreat, Euro-Atlantic circulation regimes and temperature extremes over Europe, Weather and Climate Dynamics, 4, 663–682, https://doi.org/10.5194/wcd-4-663-2023, 2023.

Risbey, J. S. and Kandlikar, M.: EXPERT ASSESSMENT OF UNCERTAINTIES IN DETECTION AND ATTRIBUTION OF CLIMATE CHANGE, Bulletin of the American Meteorological Society, 83, 1317–1326, https://doi.org/10.1175/1520-0477-83.9.1317, publisher: American Meteorological Society Section: Bulletin of the American Meteorological Society, 2002.

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., and Coumou, D.: Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia, Nature Communications, 13, 3851, https://doi.org/10.1038/s41467-022-31432-y, 2022.

Rousi, E., Fink, A. H., Andersen, L. S., Becker, F. N., Beobide-Arsuaga, G., Breil, M., Cozzi, G., Heinke, J., Jach, L., Niermann, D., Petrovic, D., Richling, A., Riebold, J., Steidl, S., Suarez-Gutierrez, L., Tradowsky, J. S., Coumou, D., Düsterhus, A., Ellsäßer, F., Fragkoulidis, G., Gliksman, D., Handorf, D., Haustein, K., Kornhuber, K., Kunstmann, H., Pinto, J. G., Warrach-Sagi, K., and Xoplaki, E.: The extremely hot and dry 2018 summer in central and northern Europe from a multi-faceted weather and climate perspective, Natural Hazards and Earth System Sciences, 23, 1699–1718, https://doi.org/10.5194/nhess-23-1699-2023, 2023.

Ruff, F. and Pfahl, S.: What distinguishes 100-year precipitation extremes over central European river catchments from more moderate extreme events?, Weather and Climate Dynamics, 4, 427–447, https://doi.org/10.5194/wcd-4-427-2023, 2023.

Rupp, S. and Damm, B.: A national rockfall dataset as a tool for analysing the spatial and temporal rockfall occurrence in Germany, Earth Surface Processes and Landforms, 45, 1528–1538, 2020.

Russo, S., Dosio, A., Graversen, R. G., Sillmann, J., Carrao, H., Dunbar, M. B., Singleton, A., Montagna, P., Barbola, P., and Vogt, J. V.: Magnitude of extreme heat waves in present climate and their projection in a warming world, Journal of Geophysical Research: Atmospheres, 119, https://doi.org/10.1002/2014JD022098, 2014.

Sairam, N., Brill, F., Sieg, T., Farrag, M., Kellermann, P., Nguyen, V. D., LÃ¼dtke, S., Merz, B., Schröter, K., Vorogushyn, S., and Kreibich, H.: Process-Based Flood Risk Assessment for Germany, Earth's Future, 9, e2021EF002 259, https://doi.org/https://doi.org/10.1029/2021EF002259, e2021EF002259 2021EF002259, 2021.

Schielicke, L. and Pfahl, S.: European heatwaves in present and future climate simulations: a Lagrangian analysis, Weather and Climate Dynamics, 3, 1439–1459, https://doi.org/10.5194/wcd-3-1439-2022, 2022.

Schwitalla, T., Warrach-Sagi, K., Wulfmeyer, V., and Resch, M.: Near-global-scale high-resolution seasonal simulations with WRF-Noah-MP v.3.8.1, Geoscientific Model Development, 13, 1959–1974, https://doi.org/10.5194/gmd-13-1959-2020, 2020.

Schwitalla, T., Jach, L., Wulfmeyer, V., and Warrach-Sagi, K.: Soil moisture–atmosphere coupling strength over central Europe in the recent warming climate, Natural Hazards and Earth System Sciences, 25, 1405–1424, https://doi.org/10.5194/nhess-25-1405-2025, 2025.

https://doi.org/10.5194/egusphere-2026-2697
Preprint. Discussion started: 12 June 2026

Schädler, G. and Breil, M.: Identification of droughts and heatwaves in Germany with regional climate networks, Nonlinear Processes in Geophysics, 28, 231–245, https://doi.org/10.5194/npg-28-231-2021, 2021.

Seneviratne, S., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Di Luca, A., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S., Wehner, M., and Zhou, B.: Weather and Climate Extreme Events in a Changing Climate, p. 1513–1766, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, https://doi.org/10.1017/9781009157896.013, 2021.

Shepherd, T. G., Boyd, E., Calel, R. A., Chapman, S. C., Dessai, S., Dima-West, I. M., Fowler, H. J., James, R., Maraun, D., Martius, O., Senior, C. A., Sobel, A. H., Stainforth, D. A., Tett, S. F., Trenberth, K. E., van den Hurk, B. J. J. M., Watkins, N. W., Wilby, R. L., and Zenghelis, D.: Storylines: an alternative approach to representing uncertainty in physical aspects of climate change, Climatic change, 151, 555–571, 2018.

Sousa, P. M., Barriopedro, D., Ramos, A. M., García-Herrera, R., Espírito-Santo, F., and Trigo, R. M.: Saharan air intrusions as a relevant mechanism for Iberian heatwaves: The record breaking events of August 2018 and June 2019, Weather and Climate Extremes, 26, 100 224, https://doi.org/10.1016/j.wace.2019.100224, 2019.

Stephenson, D. B., Diaz, H., and Murnane, R.: Definition, diagnosis, and origin of extreme weather and climate events, Climate Extremes and Society, 340, 11–23, 2008.

Suarez-Gutierrez, L., Milinski, S., and Maher, N.: Exploiting large ensembles for a better yet simpler climate model evaluation, Climate Dynamics, 57, 2557–2580, https://doi.org/10.1007/s00382-021-05821-w, 2021.

Suarez-Gutierrez, L., Müller, W. A., and Marotzke, J.: Extreme heat and drought typical of an end-of-century climate could occur over Europe soon and repeatedly, Communications Earth & Environment, 4, 415, https://doi.org/10.1038/s43247-023-01075-y, 2023.

Szemkus, S. and Friederichs, P.: Spatial patterns and indices for heat waves and droughts over Europe using a decomposition of extremal dependency, Advances in Statistical Climatology, Meteorology and Oceanography, 10, 29–49, https://doi.org/10.5194/ascmo-10-29-2024, 2024.

Thieken, A. H., Samprogna Mohor, G., Kreibich, H., and Müller, M.: Compound inland flood events: different pathways, different impacts and different coping options, Natural Hazards and Earth System Sciences, 22, 165–185, https://doi.org/10.5194/nhess-22-165-2022, 2022.

Tradowsky, J. S., Philip, S. Y., Kreienkamp, F., Kew, S. F., Lorenz, P., Arrighi, J., Bettmann, T., Caluwaerts, S., Chan, S. C., De Cruz, L., et al.: Attribution of the heavy rainfall events leading to severe flooding in Western Europe during July 2021, Climatic Change, 176, 90, 2023.

Ulbrich, U., Leckebusch, G. C., and Pinto, J. G.: Extra-tropical cyclones in the present and future climate: a review, Theoretical and Applied Climatology, 96, 117–131, https://doi.org/10.1007/s00704-008-0083-8, 2009.

Ulbrich, U., Leckebusch, G. C., and Donat, M. G.: Natural Disasters and Adaptation to Climate Change, chap. Windstorms, the Most Costly Natural Hazard in Europe, pp. 109–120, Cambridge University Press, ISBN 9781107010161, https://doi.org/10.1017/cbo9780511845710.015, 2013.

Ullrich, S. L., Hegnauer, M., Nguyen, D. V., Merz, B., Kwadijk, J., and Vorogushyn, S.: Comparative evaluation of two types of stochastic weather generators for synthetic precipitation in the Rhine basin, Journal of Hydrology, 601, 126 544, https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126544, 2021.

Van Oldenborgh, G. J., van Der Wiel, K., Kew, S., Philip, S., Otto, F., Vautard, R., King, A., Lott, F., Arrighi, J., Singh, R., et al.: Pathways and pitfalls in extreme event attribution, Climatic Change, 166, 13, 2021.

VanderWeele, T. J.: Explanation in Causal Inference: Methods for Mediation and Interaction, Oxford University Press, Oxford New York, 2015.

https://doi.org/10.5194/egusphere-2026-2697
Preprint. Discussion started: 12 June 2026

Vicente-Serrano, S. M., Beguería, S., and López-Moreno, J. I.: A Multiscalar Drought Index Sensitive to Global Warming: The Standardized Precipitation Evapotranspiration Index, Journal of Climate, 23, 1696–1718, https://doi.org/10.1175/2009JCLI2909.1, 2010.

Voit, P. and Heistermann, M.: Quantifying the extremeness of precipitation across scales, Natural Hazards and Earth System Sciences, 22, 2791–2805, https://doi.org/10.5194/nhess-22-2791-2022, 2022.

Wernli, H. and Gray, S. L.: The importance of diabatic processes for the dynamics of synoptic-scale extratropical weather systems – a review, Weather and Climate Dynamics, 5, 1299–1408, https://doi.org/10.5194/wcd-5-1299-2024, 2024.

Woollings, T., Pinto, J. G., and Santos, J. A.: Dynamical Evolution of North Atlantic Ridges and Poleward Jet Stream Displacements, Journal of the Atmospheric Sciences, 68, 954–963, https://doi.org/10.1175/2011JAS3661.1, 2011.

Xoplaki, E., Ellsäßer, F., Grieger, J., Nissen, K. M., Pinto, J. G., Augenstein, M., Chen, T.-C., Feldmann, H., Friederichs, P., Gliksman, D., Goulier, L., Haustein, K., Heinke, J., Jach, L., Knutzen, F., Kollet, S., Luterbacher, J., Luther, N., Mohr, S., Mudersbach, C., Müller, C., Rousi, E., Simon, F., Suarez-Gutierrez, L., Szemkus, S., Vallejo-Bernal, S. M., Vlachopoulos, O., and Wolf, F.: Compound events in Germany in 2018: drivers and case studies, Natural Hazards and Earth System Sciences, 25, 541–564, https://doi.org/10.5194/nhess-25-541-2025, 2025.

Zampieri, M., Ceglar, A., Dentener, F., and Toreti, A.: Wheat yield loss attributable to heat waves, drought and water excess at the global, national and subnational scales, Environ. Res. Lett., 12, https://doi.org/10.1088/1748-9326/aa723b, 2017.

Zanger, L., Bücher, A., Kreienkamp, F., Lorenz, P., and Tradowsky, J. S.: Regional pooling in extreme event attribution studies: an approach based on multiple statistical testing, Extremes, 27, 1–32, https://doi.org/10.1007/s10687-023-00480-y, 2024.

Zscheischler, J. and Fischer, E. M.: The record-breaking compound hot and dry 2018 growing season in Germany, Weather and Climate Extremes, 29, 100 270, https://doi.org/10.1016/j.wace.2020.100270, 2020.