Extreme events: from better understanding of drivers to impacts and societal adaptation

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Introduction and challenges

The 2021 unprecedented rainfalls in western Germany and the Benelux countries caused floods that killed several hundred people and destroyed entire villages. One may wonder: could the severe impacts have been prevented with better preparation and forecasting? What strategies should guide the reconstruction efforts? On the opposite side of the water spectrum, the 2022 pan-European drought and co-occurring heatwaves reduced crop yields, impaired energy production and shipping, and led to over 60,000 heat-related deaths across Europe. How likely are such events? Will they become more frequent or severe in the future? Who is most vulnerable, and what can we do to adapt?

Extreme events can disrupt socio-environmental systems with far-reaching consequences across multiple domains. Impacts are usually more severe if hazards compound each other, for instance during a concurrent drought-heatwave event or following a sequence of storms. Unexpected high societal impacts may also occur following an unfortunate combination of non-extreme drivers that affect a highly vulnerable ecological or social system. Climate change has already increased the frequency and severity of many unexpected extreme conditions.

To strengthen societal resilience in a rapidly changing environment, response and adaptation strategies must be grounded not only in a good understanding of the underlying processes driving impacts but also in deciphering potential societal responses and lessons learnt. Such a task involves unravelling interactions and feedback loops between environmental and societal drivers across multiple spatial and temporal scales, which is highly challenging.

Mission

We tackle the above challenges from a systemic and holistic perspective by leveraging a comprehensive research portfolio that encompasses diverse methods, models, scales, and domains, all while fostering long-standing stakeholder interactions at the science-society interface. Building synergies across disciplines and societal actors, we untangle drivers, quantify impacts and provide adaptation options for extreme events.

Unique selling points

In contrast to other research centres that focus on extremes, UFZ stands out for its multifaced viewpoints. We examine extreme events from both an atmospheric and an impact-centric perspective, also incorporating adaptive responses. The variety of different research foci is complemented by a unique set of different datasets and observational campaigns. Bringing the diverse expertise behind these viewpoints together, we build a comprehensive understanding of high-impact weather and climate events today and in the future. Three areas deserve to be especially highlighted: UFZ’s expertise in the emerging field of compound event research, the application of computational environmental sociology to reveal extreme event impacts, and our modelling approaches of the coupled hydrologic-economic system. These strands of research are highly unique and offer unprecedented research opportunities.

Results, products, outreach and impact

To achieve our research mission, we utilize various datasets, including weather and land surface observations (e.g., temperature, precipitation, energy and carbon fluxes, soil moisture); runoff and water quality parameters; reanalysis data; climate model simulations; and newspaper article databases. Statistical and machine learning-based analyses of existing datasets are further extended and complemented with tailored simulations of process models (mHM, mQM, FORMIND, and SPITFIRE) and dedicated observational campaigns (MOSES) to gain a deeper understanding of extreme events, their driving processes and impacts.

We quantify the likelihood of extreme and compound events based on hydrometeorological variables (including droughts, heatwaves, compound hot-dry events, spatially compounding droughts and floods) under present climate and different future socioeconomic scenarios (**CHS** [1-5]). For selected high-impact events, we attribute the event magnitude and frequency to anthropogenic climate change (**CHS**). For instance, we demonstrated that anthropogenic climate change contributed more than 25% to the 2022 European drought intensity and spatial extent [6]. We further identify the processes behind hazards such as floods and how they might be affected by climate change (**CHS, CATHYD** [7-9]). For instance, our research has revealed that shifts in flood generation processes contribute more to the occurrence of flood anomalies in Europe than changes in extreme rainfall amounts [8].

As the link between weather extremes and impacts is rather complex, we also characterize extremes in impact indicators such as soil temperature (**RS** [10]) and water quality variables (such as harmful algal blooms) in lakes and rivers (**ASAM, HDG**, **SEEFO** [11-12]). Going further along the impact chain, we develop methods to identify which combinations of weather conditions lead to large environmental impacts such as extreme wildfires, forest mortality, and crop failure (**CHS, OESA, RS** [13,14]). To assess the societal impacts of recent extreme events, we make use of household surveys and data mining of large-scale text datasets (**SUSOZ** [15,16]), for instance, to quantify the cascading impacts of Germany's 2018-2022 multi-year drought through different societal domains [17,18]. We also investigate how different adaptation strategies can help mitigate future impacts, including agricultural adaptation, innovative communication, and urban blue-green infrastructures (**OEKON**, **SUSOZ, UPR**). Using a coupled hydro-meteorological-societal response-model, we disentangled fundamental system feedbacks and suggested solutions to stabilise water supply in water scare areas [19].

To maximize the societal impact of our research, we established trustful and long-term relationships with a wide range of stakeholders and produced specific outputs that support policy-making processes. In this context, the German drought monitor serves as an essential resource for agencies at different governance levels and the general public (**CHS**). Furthermore, we actively contribute to initiatives like the *Nationale Wasserstrategie* and the management of the reservoir Rappbode, both built upon UFZ-led research on extreme events. We also support the state of Thuringia in developing its low-water/drought strategy and cooperate with affected communities and administrations in North Rhine-Westphalia and Rhineland-Palatinate to rebuild more resiliently after the 2021 flood (**SUSOZ**).

Outlook

So far, the research on extremes at UFZ is still fairly separated into different departments and Research Units. In the near future, we strive for a better integration by fostering collaborations and creating synergies across disciplines and domains. Potential avenues include (1) advancing a fully coupled hydro-economic model for Germany to project future drought impacts and how they can be reduced through different adaptation options; (2) a coupled near-realtime monitoring of how hydro-social impacts of extreme events co-evolve with adaptation efforts over time; (3) quantifying how climate drivers may be compounded by human management to create extreme impacts (for instance, meteorological drought combined with excess irrigation).

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