# Challenges and Opportunities for Understanding Societal Impacts of Climate Extremes

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**Abstract.** Climate extremes exact a heavy toll on society, with adverse impacts unequally distributed across populations. In this perspective, we outline key challenges and opportunities for advancing research on understanding societal impacts of climate extremes. We identify three key challenges: limited availability and quality of impact data, difficulties in understanding the processes leading to impacts and lack of reliable impact projections. We argue that there is a window of opportunity to address several dimensions of these challenges, and we highlight recent examples and ongoing developments that hold transformative potential for the research field. We conclude with a call to build momentum by fostering interdisciplinary research and collaboration across sectors.

## 1 Introduction

Climate extremes have caused over 2 million fatalities and losses of $ 4.3 trillion globally in the past 5 decades (WMO, 2023). For example, Cyclone Nargis resulted in over 130,000 deaths in Myanmar in 2008 (Fritz *et al.*, 2009), there were over 62,000 heat-related deaths in Europe during summer 2024 (Janoš *et al.*, 2025), and losses from the Los Angeles wildfires in early 2025 are likely to exceed $ 100 billion (Li and Yu, 2025). Reported economic losses are primarily concentrated in developed economies, whereas reported fatalities occur overwhelmingly in developing economies (WMO, 2023). Moreover, climate extremes can trigger a variety of indirect and cascading impacts which are difficult to quantify (*e.g.* de Brito *et al.*, 2024). Many of these adverse impacts are mediated by societal processes and result from complex cascades of events (*e.g.* Fritz *et al.*, 2009; Balch *et al.*, 2020; Rusca *et al.*, 2021), whose understanding requires frameworks integrating natural and human systems.

Preparedness measures for climate extremes are saving thousands of lives, yet the cost of climate-related disasters increases steadily (WMO, 2023). This trend is expected to persist in the future, as many climate extremes become more frequent and/or severe due to anthropogenic climate change (Seneviratne *et al.*, 2021). The result is a growing societal and scientific awareness of climate extremes and their impacts. Climate extremes are perceived as the top-ranked global risk in the coming 10 years (WEF, 2025), and the European Union strategy on adaptation to climate change explicitly calls for “more and better data on climate-related risks and losses” (EC, 2021).

Understanding impacts of climate extremes thus holds enormous societal and economic value, and is a key step towards climate resilience and adaptation. Relatively recent research advances include linking forecasts of meteorological or hydrological hazards to the subsequent impacts in support of disaster risk reduction (Mertz *et al.*, 2020) and improving the understanding of how the interaction between human and natural systems shapes the characteristics and outcomes of climate extremes (Balch *et al.*, 2020). Nonetheless, there are unique challenges to understanding societal impacts of climate extremes, which hinder progress beyond the current state-of-the-art. In this paper, we outline three key challenges issuing from a natural sciences perspective, and identify opportunities to address them. We conclude with an outlook and a call-to-action to advance interdisciplinary and intersectoral research on societal impacts of climate extremes.

## 2 Challenges

We identify three overarching challenges that hinder progress in understanding past, current and future societal impacts of climate extremes: the impact data challenge; the impact process understanding challenge and the impact projection challenge (Fig. 1).

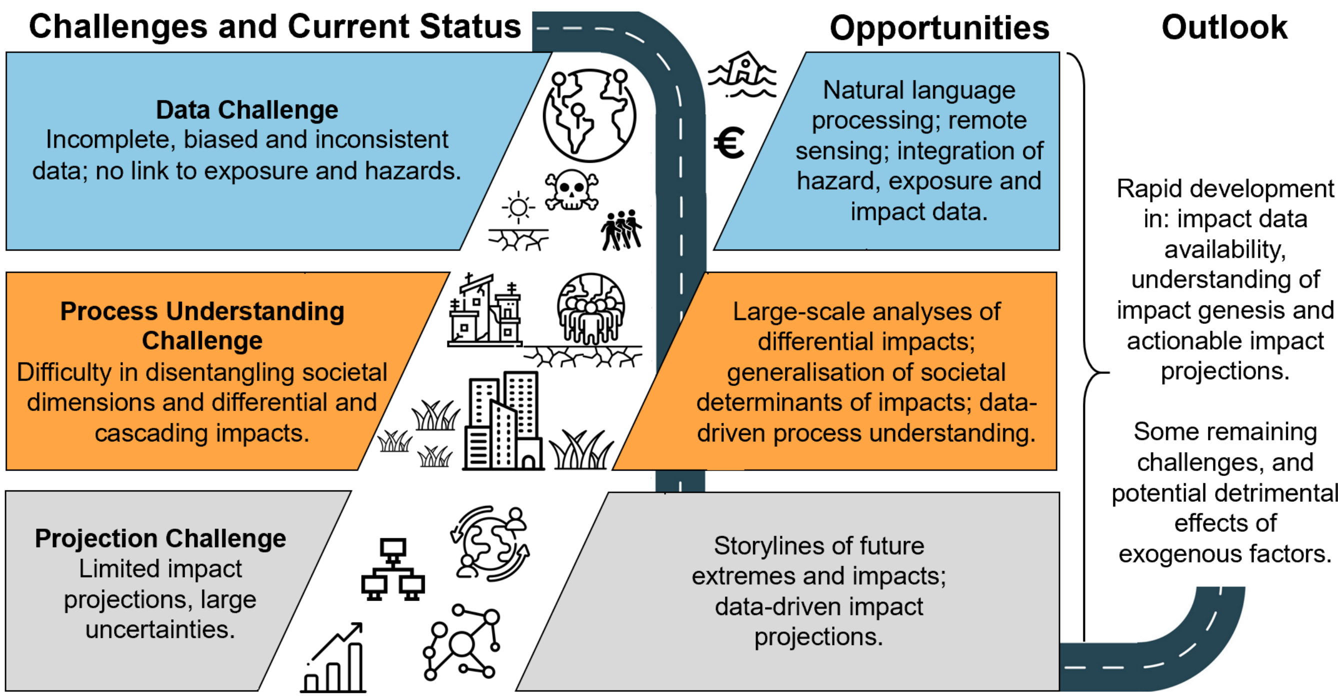

**Figure 1: Current challenges facing research on understanding impacts of climate extremes, selected opportunities for a breakthrough and outlook for the field. Images from Flaticon.com under a free use with attribution license.**

### 2.1 Data challenge

The availability and quality of impact data hinders research on impacts of climate extremes. We benefit from extensive in-situ and remote global climate observations, and their assimilation into numerical models enables physically consistent climate datasets – so-called reanalyses – providing uniform global coverage (*e.g.* Soci *et al.*, 2024). This facilitates the rapid identification and characterisation of hazardous climate extremes. However, compiling the corresponding impact data remains challenging. Most impacts cannot be quantified automatically or remotely, in contrast to how a meteorological station or a satellite may provide quantitative data on climate hazards. Moreover, many categories of societal impacts are not systematically reported. For those that are, the reporting standards can vary widely across countries or even between sources within the same country. For example, heat stress often causes fatalities by exacerbating pre-existing medical conditions, rather than being the primary cause of death. This makes it problematic to rely on cause-of-death records to quantify heat-related mortality (Longden, 2025). Similarly, impact reports for the same event may differ considerably across sources. Heavy rainfall in late 2009 and early 2010 led to severe flooding in the Kilosa district of Tanzania. The International Federation of Red Cross and Red Crescent Societies reported 50,000 people affected and 28,000 rendered homeless (IFRC, 2011). Tanzania's National Disaster Management Strategy instead listed 26,000 people affected by the same event in the same district (United Republic of Tanzania, 2022). These discrepancies are difficult to resolve due to the lack of a reliable ground truth. In the above example, it is in practice impossible to determine with certainty which estimate for the number of affected people is closer to the "true", yet unknown, figure. As a result, different impact databases often contain conflicting information (Panwar and Sen, 2019), even for well-observed hazards in developed economies (Mömken *et al.*, 2024). Moreover, some indirect or intangible impact categories are inherently hard to quantify. Climate extremes can affect human well-being and recreation (*e.g.* Niggli *et al.*, 2022; Shyrokaya *et al.*, 2023), but putting a number on these poses a conceptual problem. Additional challenges related to impact data include missing data (Jones *et al.*, 2022; 2023) and non-uniform spatial and temporal data coverage, with a bias towards events in recent decades and in developed economies (Donatti *et al.*, 2024). Finally, many disaster databases provide little or no information on the physical hazard and exposure associated with the reported impacts (Lindersson and Messori, 2025). The above data limitations hinder analyses of vulnerability, evaluation of adaptation measures, quantification of temporal trends in impacts, and the assessment of indirect and intangible impacts of non-economic loss and damage (Preston, 2017). Robust and extensive impact data is also key to effective disaster risk reduction strategies, including impact forecasting systems.

### 2.2 Process understanding challenge

Elucidating the processes leading to societal impacts of climate extremes can be challenging, even when reliable data on both the hazards and impacts is available. The impacts of a climate extreme often arise from complex interactions between biophysical, technological and societal factors (Balch *et al.*, 2020), and may cascade within and across sectors and regions (de

Brito, 2021). An example of the first is how the impacts of heavy precipitation can be radically altered by reservoir management (Di Baldassarre *et al.*, 2017). The failure of the Wivenhoe dam to alleviate the Brisbane floods of 2011 in Australia, due to operation rules prioritising water storage for drought buffering, is a case-in-point. Such societal determinants, which extend to multiple characteristics of human activities, are potentially subject to rapid changes. These can result from the implementation of new policies following catastrophic events (Fouillet *et al.*, 2008), or from personal and cultural behavioural adaptations (Ahmed *et al.*, 2025). An example of cascading impacts is the 2021 Ahr Valley floods in Germany, where flood-induced damage to transportation infrastructure impeded evacuation and restricted access to medical care (de Brito *et al.*, 2024). This cascade was mediated by the characteristics of the built environment, underscoring the complex processes leading to impacts. Moreover, the aggregated impacts for a given event often conceal how structural inequalities and pre-existing vulnerabilities shape differential impacts across populations. During recent droughts in Cape Town and Maputo, water restrictions primarily affected informal settlements and low-income households, while more affluent households experienced comparatively minor impacts (Enqvist and Ziervogel, 2019; Rusca *et al.*, 2024). This disparity is not seen in aggregated water consumption figures. Finally, a given impact can be associated with multiple connected climate hazards, often referred to as compound events (Muheki *et al.*, 2024; Jäger *et al.*, 2024; Worou and Messori, 2024). The deadly 2025 floods in Texas occurred on the background of a severe drought (NOAA, 2025), which decreased the ability of the soil to absorb water. Isolating the role of the extreme rainfall from the preconditioning effect of the drought in causing fatalities is challenging. Further complicating the picture, the connected hazards triggering large impacts can display varying levels of extremity, or in some cases not even be extreme in the statistical sense of the term (Leonard *et al.*, 2014). In 2016, northern France experienced an unprecedented wheat crop loss. This was likely due to a record-low number of cold days during winter, followed by a wet but not record-breaking spring (Pfleiderer *et al.*, 2021). As a result of these complex drivers, crop forecast models at the time were unable to predict the crop loss event (Ben-Ari *et al.*, 2018). The presence of multivariate drivers thus hinders understanding the processes underlying the impacts. The inherent complexity in understanding how and why specific climate extremes and the associated hazards result in societal impacts makes it challenging to generalise studies of vulnerability and mechanistic analyses of impact processes beyond specific locations, extreme event types and time periods. In most cases, researchers must navigate a trade-off between the spatial and temporal scope of a study and the depth of process-level understanding of the impacts.

### 2.3 Projection challenge

Projections of potential future impacts of climate extremes remain limited, even though such projections are crucial for adaptation planning amid accelerating changes in global climate and in many societies. There is extensive work on projections of future hazards related to climate extremes from global to local scales, chiefly through numerical and data-driven climate and Earth system modelling (*e.g.* Cook *et al.*, 2020; Zhao *et al.*, 2021; Sangelantoni *et al.*, 2024; Gónzalez-Abad and Gutiérrez, 2025). Considerable work has also been conducted on exposure projections for such hazards (*e.g.* Thiery *et al.*, 2021; Gampe *et al.*, 2024), and some studies – notably in the field of public health – have also dealt with future societal vulnerability (Lay *et al.*, 2021). Furthermore, there have been coordinated efforts to leverage hazard projections to model the associated impacts.

An example is the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP; Frieler *et al.*, 2024). ISIMIP provides valuable insights into the potential implications of future climate extremes. However, in many cases the ISIMIP impact models do not inform on actual impacts, but rather model derived hazards (Messori *et al.*, 2025). An example is flooding. Climate models typically output precipitation, which together with other climate variables is then translated into flooding by hydrological and flood models. However, flooding in itself is not an impact, but rather a hazard derived from precipitation. The impacts would then be for example the number of fatalities, the number of displaced people or the economic losses due to a flood. Moreover, extending the modelling chain from climate models to impact models comes at the cost of amplified uncertainty. Climate models simulate a range of possible future climates, which depend on model uncertainty, scenario uncertainty and internal climate variability (Lehner *et al.*, 2020). Any one of these different future climates can be used to force multiple impact models simulating the same impact (or derived hazard) category, which come with their own model uncertainty. As a result, quantitative impact projections are comparatively rare, and concentrated in specific sectors such as agriculture or public health (*e.g.* Quijal-Zamorano *et al.*, 2021; Slater *et al.*, 2022), although there are some counterexamples (García-León *et al.*, 2021; Severino *et al.*, 2024). With few exceptions, notably in public health, these impact projections also overlook differential impacts and how the exposure to and impacts of a given event can be modulated by societal characteristics and human activities. This lack of comprehensive and disaggregated impact projections constrains adaptation planning and policymaking, particularly by limiting the ability to quantify the implications of future climate extremes across different regions and populations for diverse socioeconomic development pathways.

## 3 Opportunities

Recent methodological and technical developments offer a window of opportunity to address the multiple challenges outlined above (Fig. 1). Some aspects of these challenges, such as the lack of ground truth information for impact data validation, are likely to persist in the future. However, there is considerable potential for rapid progress in several other aspects, which we outline below. This is not intended as a comprehensive review of all recent developments in the literature. Rather, we select some specific examples which we view as potentially transformative for research on understanding societal impacts of climate extremes.

### 3.1 Enhancing availability and interpretability of impact data

Multiple avenues offer improvements in the availability and interpretability of impact data. A large amount of information on impacts of climate extremes is contained in textual documents, making it difficult to identify and use. Automated extraction of textual information on impacts of climate extremes has been conducted for several years (*e.g.* de Brito *et al.*, 2020). However, the recent explosive development of large language models enables more extensive and detailed extraction work, including automatically compiling quantitative impact data in a format similar to that of existing manually-compiled impact databases (Li *et al.*, 2024). Related work leveraging natural language processing and machine-learning algorithms, evidences how such tools can elucidate the spatio-temporal dynamics and propagation of impacts of climate extremes (Sodoge *et al.*, 2024). The automated analysis of textual sources comes with both technical challenges and limitations in data quality. Any automated approach, including large language models, can introduce errors in the output, and thus requires robust validation through open and reproducible pipelines. Moreover, even for a "perfect" language model and postprocessing, the data will only be as good as what is in the textual source. Nonetheless, these methods enable the use of previously untapped impact data sources by the research community. Another opportunity is offered by methodological approaches for translating remotely-sensed data to impacts. Night light data has previously been linked to human displacement (Enenkel *et al.*, 2020) and its use was recently extended to estimate multiple dimensions of flood impacts (Hu *et al.*, 2024). Such approaches can help fill coverage gaps in existing impact databases, even in regions where impact reporting is incomplete or absent. A third promising development is the improved potential to connect hazards, exposure and impacts (*e.g.* Lindersson and Messori, 2025). This is facilitated by recent global climate datasets, with both longer temporal coverage (*e.g.* Soci *et al.*, 2024) and higher spatial resolution (*e.g.* Beck *et al.*, 2022) than in the past, and new global high-resolution exposure datasets (*e.g.* Kummu *et al.*, 2025). Such data enable studying vulnerabilities at regional-to-local scale, while also conducting multi-country analyses. They also support the development of effective impact forecasting.

### 3.2 Advancing understanding of processes leading to impacts

There are several new opportunities for better understanding the processes leading from climate extremes to societal impacts. First, the improved data availability outlined above supports large-scale analyses which investigate differential impacts (*e.g.* Wang *et al.*, 2025). These new data also enable highly-resolved analyses of local differential impacts across large numbers of extreme events. A second opportunity comes from the gathered experience of collaboration between the social and natural sciences on impacts of climate extremes. The large number of case studies and theoretical analyses conducted on the topic enable identifying common patterns and generalisable elements, applicable across a broad range of contexts (Rusca *et al.*, 2021; Kuhlicke *et al.*, 2023; Rusca *et al.*, 2023). We particularly highlight recent applications integrating quantitative and qualitative data, through approaches such as system dynamics models and agent-based models (Colon *et al.*, 2021; Mazzoleni *et al.*, 2024). The field of sociohydrology has been pioneering a connected line of work for over a decade (Sivapalan *et al.*, 2014; Di Baldassarre *et al.*, 2015). This has included analyses of how structural inequalities driven by power asymmetries can lead to parts of society having lower adaptive capacity, higher vulnerability and ultimately experiencing larger impacts (*e.g.* Lindersson *et al.*, 2023). We now see the opportunity for a broader applicability of similar interdisciplinary approaches across multiple climate extremes and impacts. A third promising avenue lies in applying data-driven methods to elucidate how intersecting vulnerabilities (*e.g.* age, income, ethnicity, legal status) shape differential exposure and impacts of climate extremes. These methods help capture structural inequalities, and have recently been applied in other field such as the study of health risk behaviours (McCabe *et al.*, 2025).

### 3.3 Innovations in projecting future impacts

We see a strong potential for innovation in projecting future impacts. Quantitative deterministic or probabilistic projections come with inherent limitations. The first risk giving a false sense of certainty, by being “precisely wrong”. The second may not fully characterise uncertainty, and are challenging to interpret and to translate into concrete policy or adaptation actions (Shepherd *et al.*, 2018). There have indeed been claims that a formal probabilistic assessment of the risk associated with climate change is virtually impossible (van den Hurk *et al.*, 2023). While continued development of process-based impact models is valuable, we thus argue for the need to complement such models with non-probabilistic approaches such as “storylines”, namely narratives of plausible future events. Storylines initially focused on physical climate hazards, building on climate model simulations to develop “tales of future weather” (Hazeleger *et al.*, 2015), including plausible outcomes of regional climate change (Levine *et al.*, 2024; Klimiuk *et al.*, 2025). Building on this, the storyline paradigm has been expanded to combine quantitative climate information with the societal factors that shape the impacts of climate extremes (Rusca *et al.*, 2021; van den Hurk *et al.*, 2023). Recent work has developed guidelines for the use of storylines by humanitarian practitioners (Jack *et al.*, 2024), frameworks for plural storylines that incorporate local knowledge and societal justice considerations (Rusca *et al.*, 2024) and storylines that consider the role of infrastructure in modulating future climate impacts (Goulart *et al.*, 2025). The storyline canon thus enables combining the societal dimension and the anthroposphere with projections of future climate extremes, and accounting for multiple hazards, differential vulnerabilities and impacts and complex impact cascades (Rusca *et al.*, 2023; Raffetti *et al.*, 2024). The storylines’ usefulness and usability can be maximised by continued cross-pollination among different approaches and research fields (Baulenas *et al.*, 2023). Storylines thus complement quantitative, process-based projections of future impacts of climate extremes by providing situated and actionable information, which is accessible to non-specialist users. Actionable and locally relevant information on future impacts can also be obtained by reversing the conventional impact quantification chain, for example linking specific local climate risk thresholds associated with large impacts to climate change scenarios (Pfleiderer *et al.*, 2025). A radically different, but equally promising opportunity lies in the use of data-driven approaches for estimating future impacts of climate extremes. These have seen relatively widespread adoption in specific subfields, such as for crop yield projections (*e.g.* Taniushkina *et al.*, 2024), but are yet to be widely implemented for climate-related societal impacts. There is however great potential, including for estimating indirect impacts (*e.g.* Qiu *et al.*, 2024). A third promising development is the integration of human dynamics in Earth System Models (Tapiador and Navarro, 2024), enabling to resolve the two-way interactions between future climate extremes and societal dynamics, which in turn modulate climate impacts. The above approaches above are highly complementary: storylines provide context-specific and locally grounded insights, while numerical and data-driven impact projections can offer a large-scale perspective. Moreover, the latter can inform the former.

Some of the above opportunities – such as those issuing from the processing of textual data with large language models – are already being exploited. Others – such as the use of high-resolution hazard and exposure data for global intercomparisons of local-scale vulnerability – remain promising possibilities. Even in the first cases, the potential of these new research avenues is far from having been leveraged in full.

## 4 Outlook and call to action

Understanding the impacts of climate extremes requires multidisciplinary efforts to account for natural and human systems, and their interplay. The topic holds significant societal and economic value, yet faces distinctive challenges which partly stem from its positioning at the interface of different disciplines. In this paper, we identified three such challenges issuing from a natural sciences perspective: the impact data challenge, the impact process understanding challenge, and the impact projection challenge (Fig. 1). These challenges hinder both scientific development in the field, and the practical usability of research findings.

Nonetheless, we see reason for cautious optimism. Newly released datasets and recent methodological and technical advances open a window of opportunity to address several dimensions of the challenges that we have identified here. Notable examples include extracting impact information from textual sources using large language models and developing impact projections using data-driven approaches. Moreover, interdisciplinary collaborations between the social and natural sciences can elucidate processes underlying past climate impacts and enable building storylines of future societal impacts.

This optimism should however not be naïve. Some dimensions of the challenges that we outline are structural and unlikely to be resolved in the near-term. An example is the lack of ground truth information to validate discrepant impact data. We should also be wary of the "perfect tomorrow" fallacy, namely of delaying investigations indefinitely, waiting for better impact data and analysis tools to become available. While current data and analysis approaches do have limitations, there is much valuable research that can still be performed on understanding societal impacts of climate extremes, even in the absence of major data and methodological developments. Exogenous factors that we have not discussed in detail can also modulate advances in the field. A growing concern is the ongoing privatisation of climate impact data, with the climate risk analytics market growing into a multi-billion dollar industry (Mankin, 2024). The private sector can provide added value to research on climate impacts, but it is important that data developed by the private sector remains accessible for non-commercial research. Else, the risk is that only some parts of society will benefit from it and successfully adapt to future climate extremes, while others may be left behind.

Here, we focused on understanding the societal impacts of climate extremes. However, several of the challenges and opportunities that we outline apply more generally to the study of hazardous environmental events and their impacts on natural and human systems. These hazardous events may or may not be "extreme" in the conventional meaning of the term, and indeed both events of moderate physical magnitude (McPhillips *et al.*, 2018) and slow-onset events (Van Der Geest *et al.*, 2021) can result in large impacts.

A holistic understanding of the multifaceted impacts of climate extremes, of the biophysical, technological and societal factors shaping such impacts, and projections of potential future impacts, are valuable tools to ensure just and resilient societies in the face of a changing climate. We therefore call for building momentum in seizing the many methodological, technical and collaborative opportunities now emerging for a breakthrough in the study of impacts of climate extremes. Achieving meaningful progress will require interdisciplinary and intersectoral research, and strong collaboration across academic, policy and practitioner communities.

**Code availability.** No code was generated as part of this study.

**Data availability.** No data was used in this study.

**Author contributions.** GM conceived and wrote the original draft, the revised draft and produced the figure. All authors contributed to reviewing and updating the text and figure.

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