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 elucidating the genesis of 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 47,000 heat-related deaths in Europe during summer 2023 (Gallo *et al.*, 2023), 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). 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).

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

35 (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. Recent research advances include the linkage of meteorological or hydrological forecasts to impacts in support of disaster risk reduction (Mertz *et al.*, 2020) and improved understanding of how humans shape the characteristics

40 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

45 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 genesis challenge and the impact projection challenge (Fig. 1).
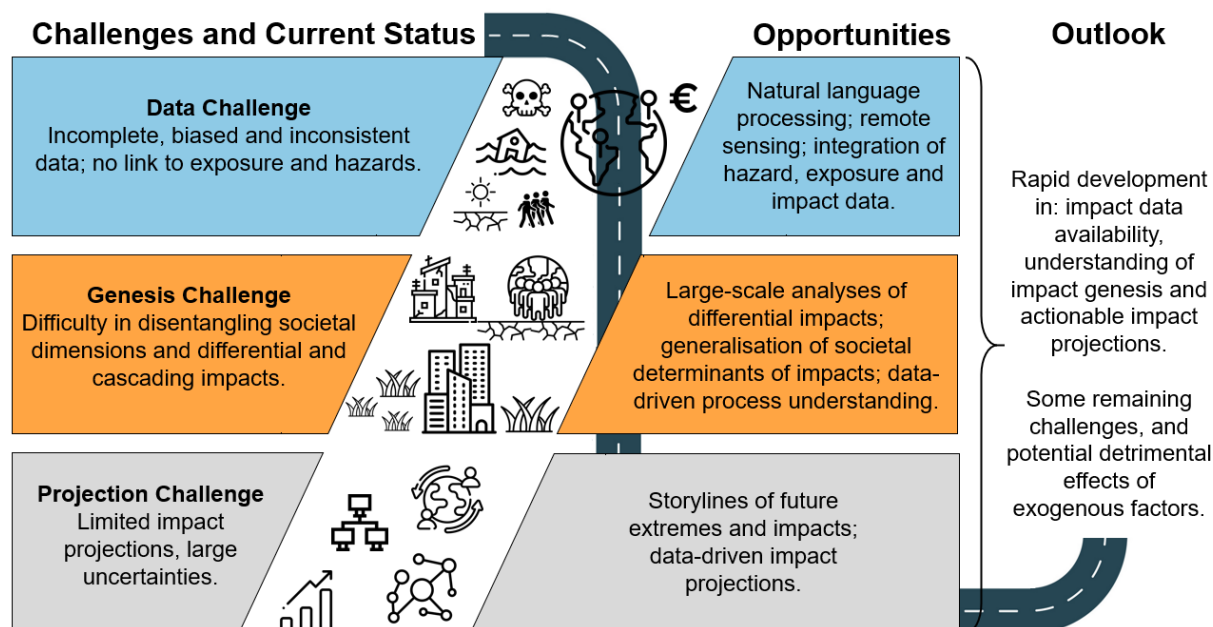

Figure 1: Current challenges facing research on understanding impacts of climate extremes, selected opportunities for a breakthrough and outlook for the field. Images from Flaticon.com under a free use with attribution license.

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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 providing uniform global coverage (e.g. Soci *et al.*, 2024). This facilitates the rapid identification and characterisation

55   of hazardous climate events. 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.

60   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).

65   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

70   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

75   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 Genesis challenge

Elucidating the genesis of societal impacts of climate extremes can be challenging, even when reliable data on both the hazards

80   and impacts is available. The impacts of a climate extreme often arise from complex interactions between biophysical and societal factors (Balch *et al.*, 2020), and may cascade within and across sectors and regions (de Brito, 2021). One 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, due to operation rules prioritising water storage for drought buffering, is a case-in-point. Such societal determinants are potentially subject to rapid changes, for

85   example through the implementation of new policies following catastrophic events (Fouillet *et al.*, 2008). 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). Moreover, the aggregated impacts for a given

event often conceal how pre-existing vulnerabilities shape differential impacts across populations. Recent droughts in Cape Town and Maputo illustrate that water restrictions primarily affected informal settlements and low-income households, while

90 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, also termed compound events (Muheki *et al.*, 2024; Jäger *et al.*, 2024). This hinders a univocal categorisation of the impact's root cause. For instance, 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. This makes it difficult to isolate the role of the

95 extreme rainfall from the preconditioning effect of the drought in causing fatalities. The inherent complexity in understanding how and why specific hazards result in societal impacts makes it challenging to generalise studies of vulnerability and mechanistic analyses of impact genesis 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.

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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 climate extremes from global to local scales, chiefly through numerical and data-driven modelling of the climate and

105 Earth systems (*e.g.* Cook *et al.*, 2020; Zhao et al., 2021; Sangelantoni *et al.*, 2024). Considerable work has also been conducted on exposure projections for multiple climate extremes (*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

110 of future climate extremes. However, in many cases the ISIMIP models do not inform on 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

115 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.*,

120 2022), although there are some counterexamples (García-León *et al.*, 2021; Severino *et al.*, 2024). With few exceptions, notably public health, impact projections generally overlook differential impacts. 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.

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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

130   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

135   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

140   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 – since even for a "perfect" language model and postprocessing pipeline, 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

145   new opportunity is offered by methodological approaches for translating remotely-sensed data to impacts. A recent example is the use of night light data to estimate 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*

150   *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 impact genesis

155   There are several new opportunities for better understanding the genesis of impacts of climate extremes. 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

160   common patterns and generalisable elements, applicable across a broad range of contexts (Rusca *et al.*, 2021; Kuhlicke *et al.*,
2023). 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), and 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

165   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

170   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). This has motivated the development of so-called "storylines", namely non-probabilistic 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

175   al.*, 2024; Klimiuk *et al.*, 2025). Building on this, the storyline paradigm has been expanded to include 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) and frameworks for plural storylines that incorporate
local knowledge and societal justice considerations (Rusca *et al.*, 2024). The storyline canon provides a powerful tool to
combine the human and societal perspective with numerical projections of climate extremes, and enables accounting for

180   multiple hazards, differential impacts and complex impact cascades (Rusca *et al.*, 2023; Raffetti *et al.*, 2024). It also provides
situated and actionable information, which is accessible to non-specialist users. Storylines can thus provide an effective
complement to the ongoing efforts to develop numerical projections of future impacts. Their usefulness and usability can be
maximised by continued cross-pollination among different approaches and research fields (Baulenas *et al.*, 2023). A radically
different, but equally promising opportunity lies in the use of data-driven approaches for estimating future impacts of climate

185   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). The two approaches above are highly

complementary: storylines provide context-specific and locally grounded insights, while data-driven impact projections can offer a large-scale perspective.

190 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.

195   **4   Outlook and call to action**

Understanding the impacts of climate extremes holds significant societal and economic value, yet faces distinctive challenges. In this paper, we identified three such challenges issuing from a natural sciences perspective: the impact data challenge, the impact genesis challenge, and the impact projection challenge (Fig. 1). These challenges hinder both scientific development in the field, and the practical usability of research findings.

200 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 the genesis of past climate impacts and enable building storylines of future societal impacts.

205 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

210 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

215 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 even events of moderate physical magnitude can result in large impacts (McPhillips *et al.*, 2018).

220 A holistic understanding of the multifaceted impacts of climate extremes, of the biophysical and societal factors shaping their genesis, and 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.

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References

Balch, J. K., Iglesias, V., Braswell, A. E., Rossi, M. W., Joseph, M. B., Mahood, A. L., ... & Travis, W. R. (2020). Social-environmental extremes: Rethinking extraordinary events as outcomes of interacting biophysical and social systems. *Earth's Future*, *8*(7), e2019EF001319.
240
Baulenas, E., G. Versteeg, M. Terrado, J. Mindlin, D. Bojovic, Assembling the climate story: use of storyline approaches in climate-related science. Global Challenges 2023, 7, 2200183. https://doi.org/10.1002/gch2.202200183

Di Baldassarre, G., Viglione, A., Carr, G., Kuil, L., Yan, K., Brandimarte, L., & Blöschl, G. (2015). Debates—Perspectives
245 on socio-hydrology: Capturing feedbacks between physical and social processes. *Water Resources Research*, *51*(6), 4770-4781.

Di Baldassarre, G., Martinez, F., Kalantari, Z., & Viglione, A. (2017). Drought and flood in the Anthropocene: feedback mechanisms in reservoir operation. *Earth System Dynamics*, *8*(1), 225-233.
250
Beck, H. E., Van Dijk, A. I., Larraondo, P. R., McVicar, T. R., Pan, M., Dutra, E., & Miralles, D. G. (2022). MSWX: Global 3-hourly 0.1 bias-corrected meteorological data including near-real-time updates and forecast ensembles. *Bulletin of the American Meteorological Society*, *103*(3), E710-E732.

255 Beven, K., Lamb, R., Leedal, D., & Hunter, N. (2015). Communicating uncertainty in flood inundation mapping: a case study. *International Journal of River Basin Management*, *13*(3), 285-295.

de Brito, M. M., Kuhlicke, C., & Marx, A. (2020). Near-real-time drought impact assessment: a text mining approach on the 2018/19 drought in Germany. *Environmental Research Letters*, *15*(10), 1040a9.

260 de Brito, M. M. (2021). Compound and cascading drought impacts do not happen by chance: A proposal to quantify their relationships. *Science of the Total Environment*, *778*, 146236.

de Brito, M. M., Sodoge, J., Fekete, A., Hagenlocher, M., Koks, E., Kuhlicke, C., ... & Ward, P. J. (2024). Uncovering the
265 dynamics of multi-sector impacts of hydrological extremes: A methods overview. *Earth's Future*, *12*(1), e2023EF003906.

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E., & Anchukaitis, K. J. (2020). Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Future*, *8*(6), e2019EF001461.

270 Donatti, C. I., Nicholas, K., Fedele, G., Delforge, D., Speybroeck, N., Moraga, P., ... & Zvoleff, A. (2024). Global hotspots of climate-related disasters. *International Journal of Disaster Risk Reduction*, *108*, 104488.

EC: European Commission (2021). EU Adaptation Strategy. Accessed at: https://climate.ec.europa.eu/eu-action/adaptation-climate-change/eu-adaptation-strategy_en on 02-07-2025
275

Enqvist, J. P., & Ziervogel, G. (2019). Water governance and justice in Cape Town: An overview. Wiley Interdisciplinary Reviews: Water, 6(4), e1354.

Fouillet, A., Rey, G., Wagner, V., Laaidi, K., Empereur-Bissonnet, P., Le Tertre, A., ... & Hémon, D. (2008). Has the impact
280 of heat waves on mortality changed in France since the European heat wave of summer 2003? A study of the 2006 heat wave. *International journal of epidemiology*, *37*(2), 309-317.

Frieler, K., Volkholz, J., Lange, S., Schewe, J., Mengel, M., del Rocío Rivas López, M., ... & Bechtold, M. (2024). Scenario setup and forcing data for impact model evaluation and impact attribution within the third round of the Inter-Sectoral Impact
285 Model Intercomparison Project (ISIMIP3a). *Geoscientific Model Development*, *17*(1), 1-51.

Fritz, H. M., Blount, C. D., Thwin, S., Thu, M. K., & Chan, N. (2009). Cyclone Nargis storm surge in Myanmar. *Nature Geoscience*, *2*(7), 448-449.

290 Gallo, E., Quijal-Zamorano, M., Méndez Turrubiates, R. F., Tonne, C., Basagaña, X., Achebak, H., & Ballester, J. (2024). Heat-related mortality in Europe during 2023 and the role of adaptation in protecting health. *Nature medicine*, 30, 3101–3105.

Gampe, D., Schwingshackl, C., Böhnisch, A., Mittermeier, M., Sandstad, M., and Wood, R. R.: Applying global warming levels of emergence to highlight the increasing population exposure to temperature and precipitation extremes, Earth Syst.
295 Dynam., 15, 589–605, https://doi.org/10.5194/esd-15-589-2024, 2024.

García-León, D., Casanueva, A., Standardi, G. *et al.* Current and projected regional economic impacts of heatwaves in Europe. *Nat Commun* **12**, 5807 (2021). https://doi.org/10.1038/s41467-021-26050-z

300 Hazeleger, W. et al. (2015) Tales of future weather. *Nat. Clim. Change* **5**, 107–113.

Hu, Y., Yamazaki, D., Zhou, X., & Zhao, G. Flood Impact Assessment Using Nighttime Light Remote Sensing Data. *Preprint*, *SSRN 5011700*.

305 van den Hurk, B. J., Pacchetti, M. B., Boere, E., Ciullo, A., Coulter, L., Dessai, S., ... & Witpas, K. (2023). Climate impact storylines for assessing socio-economic responses to remote events. Climate Risk Management, 40, 100500.

IFRC: International Federation of Red Cross and Red Crescent Societies (2011) Final Report Tanzania: Floods. Emergency appeal n° MDRTZ010 GLIDE n° FL-2009-000264-TZA. Accessed at:
310   https://www.ifrc.org/docs/appeals/10/MDRTZ010fr.pdf Accessed on 02-07-2025

Jack, C., Korodimou, M., Vogel, M., Heinrich, D., Jaime, C., & El Hajj, R. (2024). Climate risk storylines: Navigating the uncertainties of climate change: Guidelines for humanitarian practitioners. Red Cross Red Cresent Climate Centre.

315   Jones, R.L., Guha-Sapir, D. & Tubeuf, S. (2022) Human and economic impacts of natural disasters: can we trust the global data?. *Sci Data* **9**, 572.

Jones, R. L., Kharb, A., & Tubeuf, S. (2023). The untold story of missing data in disaster research: a systematic review of the empirical literature utilising the Emergency Events Database (EM-DAT). *Environmental Research Letters*, *18*(10), 103006.
320

Jäger, W. S., de Ruiter, M. C., Tiggeloven, T., & Ward, P. J. (2024). What can we learn from global disaster records about multi-hazards and their risk dynamics?. *Natural Hazards and Earth System Sciences Discussions*, *2024*, 1-31.

Klimiuk, T., Ludwig, P., Sanchez-Benitez, A., Goessling, H. F., Braesicke, P., and Pinto, J. G.: The European summer
325   heatwave of 2019 – a regional storyline perspective, Earth Syst. Dynam., 16, 239–255, https://doi.org/10.5194/esd-16-239-2025, 2025.

Kuhlicke, C., de Brito, M. M., Bartkowski, B., Botzen, W., Doğulu, C., Han, S., et al. (2023). Spinning in circles? A systematic review on the role of theory in social vulnerability, resilience and adaptation research. *Global Environmental Change*, 80,
330   102672. https://doi.org/10.1016/j.gloenvcha.2023.102672

Kummu, M., Kosonen, M., & Masoumzadeh Sayyar, S. (2025). Downscaled gridded global dataset for gross domestic product (GDP) per capita PPP over 1990–2022. *Scientific Data*, *12*(1), 178.

335   Lay, C. R., Sarofim, M. C., Zilberg, A. V., Mills, D. M., Jones, R. W., Schwartz, J., & Kinney, P. L. (2021). City-level vulnerability to temperature-related mortality in the USA and future projections: a geographically clustered meta-regression. *The Lancet Planetary Health*, *5*(6), e338-e346.

Lehner, F., Deser, C., Maher, N., Marotzke, J., Fischer, E. M., Brunner, L., Knutti, R., and Hawkins, E. (2020) Partitioning
340   climate projection uncertainty with multiple large ensembles and CMIP5/6, *Earth Syst. Dynam.*, 11, 491–508, https://doi.org/10.5194/esd-11-491-2020.

Levine, X. J., Williams, R. S., Marshall, G., Orr, A., Seland Graff, L., Handorf, D., Karpechko, A., Köhler, R., Wijngaard, R. R., Johnston, N., Lee, H., Nieradzik, L., and Mooney, P. A.: Storylines of summer Arctic climate change constrained by
345   Barents–Kara seas and Arctic tropospheric warming for climate risk assessment, Earth Syst. Dynam., 15, 1161–1177, https://doi.org/10.5194/esd-15-1161-2024, 2024.

Li, N., Zahra, S., de Brito, M.M., Flynn, C.M., Görnerup, O., Worou, K., Kurfalı, M., Meng, C., Thiery, W., Zscheischler, J., Messori, G., Nivre, J. (2024), Using LLMs to Build a Database of Climate Extreme Impacts. Proceedings of Natural Language
350   Processing meets Climate Change @ ACL 2024, Association for Computational Linguistics.

Li, Z., & Yu, W. (2025). *Economic impact of the Los Angeles wildfires*. Technical Report 2025. Accessed at: https://www. anderson. ucla. edu/about/centers/ucla-anderson-forecast/economic-impact-los-angeles-wildfires on 2025-03-19.

355   Lindersson, S., & Messori, G. (2025). SHEDIS-Temperature: Linking temperature-related disaster impacts to subnational data on meteorology and human exposure. *Earth System Science Data Discussions*, *2025*, 1-30.

Longden, T. (2025). Underestimating heat-related mortality—a comparison of excess mortality and death record studies for Australia. *The Lancet Regional Health–Western Pacific*, 58.

360

Mankin, J. S. (2024). The People Have a Right to Climate Data. *International New York Times*. Accessed at: https://www.nytimes.com/2024/01/20/opinion/climate-risk-disasters-data.html on 02-07-2025

McCabe, C. J., Helm, J. L., Halvorson, M. A., Blaikie, K. J., Lee, C. M., & Rhew, I. C. (2025). Estimating substance use
365   disparities across intersectional social positions using machine learning: An application of group-lasso interaction network. *Psychology of Addictive Behaviors*, 39(2), 113–126. https://doi.org/10.1037/adb0001020

McPhillips, L. E., Chang, H., Chester, M. V., Depietri, Y., Friedman, E., Grimm, N. B., ... & Shafiei Shiva, J. (2018). Defining extreme events: A cross-disciplinary review. *Earth's Future*, 6(3), 441-455.

370

Merz, B., Kuhlicke, C., Kunz, M., Pittore, M., Babeyko, A., Bresch, D. N., ... & Wurpts, A. (2020). Impact forecasting to support emergency management of natural hazards. *Reviews of geophysics*, *58*(4), e2020RG000704.

Messori, G., Muheki, D., Batibeniz, F., Bevacqua, E., Suarez-Gutierrez, L., & Thiery, W. (2025). Global mapping of
375   concurrent hazards and impacts associated with climate extremes under climate change. *Earth's Future*, 13, e2025EF006325. https://doi.org/10.1029/2025EF006325

Moemken, J., Messori, G., & Pinto, J. G. (2024). Windstorm losses in Europe–What to gain from damage datasets. *Weather and Climate Extremes*, *44*, 100661.

380

Muheki, D., Deijns, A. A. J., Bevacqua, E., Messori, G., Zscheischler, J., and Thiery, W.: The perfect storm? Co-occurring climate extremes in East Africa, Earth Syst. Dynam., 15, 429–466, https://doi.org/10.5194/esd-15-429-2024, 2024.

NOAA (2025). Looking Ahead at Summer Drought in 2025. Accessed at: https://www.drought.gov/news/looking-ahead-
385   summer-drought-2025-05-28 on 16-07-2025

Panwar, V., & Sen, S. (2019). Economic impact of natural disasters: An empirical re-examination. *Margin: The Journal of Applied Economic Research*, *13*(1), 109-139.

390   Preston, C. J. (2017). Challenges and opportunities for understanding non-economic loss and damage. Ethics, Policy & Environment, 20(2), 143-155.

Quijal-Zamorano, M., Martinez-Solanas, E., Achebak, H., Petrova, D., Robine, J. M., Herrmann, F. R., et al. (2021). Seasonality reversal of temperature attributable mortality projections due to previously unobserved extreme heat in Europe.
395   *The Lancet Planetary Health*, 5(9), e573–e575. https://doi.org/10.1016/s2542-5196(21)00211-4

Qiu, M., Li, J., Gould, C. F., Jing, R., Kelp, M., Childs, M., ... & Burke, M. (2024). *Mortality burden from wildfire smoke under climate change* (No. w32307). National Bureau of Economic Research.

400   Raffetti, E., Ahrne, M., Döring, S., Hagström, A., Mazzoleni, M., Messori, G., ... & Zarantonelllo, L. (2024). Sustainable transformations for healthcare systems in a changing climate. *Cell Reports Sustainability*, *1*(3).

Rusca, M., Messori, G., & Di Baldassarre, G. (2021). Scenarios of human responses to unprecedented social-environmental extreme events. *Earth's Future*, *9*(4), e2020EF001911.

405

Rusca, M., Savelli, E., Di Baldassarre, G. *et al.* (2023) Unprecedented droughts are expected to exacerbate urban inequalities in Southern Africa. *Nat. Clim. Chang.* **13**, 98–105.

Rusca, M., Sverdlik, A., Acharya, A. *et al.* Plural climate storylines to foster just urban futures. *Nat Cities* **1**, 732–740 (2024). https://doi.org/10.1038/s44284-024-00133-6

Sangelantoni, L., Sobolowski, S., Lorenz, T., Hodnebrog, Ø., Cardoso, R. M., Soares, P. M., ... & Bastin, S. (2024). Investigating the representation of heatwaves from an ensemble of km-scale regional climate simulations within CORDEX-FPS convection. *Climate dynamics*, *62*(6), 4635-4671.

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., Luca, A. D., Ghosh, S., Iskandar, I., Kossin, J., Lewis, S., Otto, F., Pinto, I., Satoh, M., Vicente-Serrano, S. M., Wehner, M., Zhou, B. and Allan, R. (2021) *Weather and climate extreme events in a changing climate.* In: Masson-Delmotte, V. P., Zhai, A., Pirani, S. L. and Connors, C. (eds.) Climate Change 2021: The Physical Science Basis: Working Group I contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK, pp. 1513-1766.

Severino, L. G., Kropf, C. M., Afargan-Gerstman, H., Fairless, C., de Vries, A. J., Domeisen, D. I. V., & Bresch, D. N. (2024). Projections and uncertainties of winter windstorm damage in Europe in a changing climate. *Natural Hazards and Earth System Sciences*, 24(5), 1555–1578. https://doi.org/10.5194/nhess-24-1555-2024

Shepherd, T. G. et al (2018) Storylines: an alternative approach to representing uncertainty in physical aspects of climate change. *Climatic Change* **151**, 555–571.

Shyrokaya, A., Messori, G., Pechlivanidis, I., Pappenberger, F., Cloke, H. L., & Di Baldassarre, G. (2023). Significant relationships between drought indicators and impacts for the 2018–2019 drought in Germany. *Environmental Research Letters*, *19*(1), 014037.

Sivapalan, M., M. Konar, V. Srinivasan, A. Chhatre, A. Wutich, C. A. Scott, J. L. Wescoat, and I. Rodríguez-Iturbe (2014), Socio-hydrology: Use-inspired water sustainability science for the Anthropocene, Earth's Future, 2, doi:10.1002/2013EF000164.

Slater, L. J., Huntingford, C., Pywell, R. F., Redhead, J. W., and Kendon, E. J. (2022) Resilience of UK crop yields to compound climate change, *Earth Syst. Dynam.*, 13, 1377–1396, https://doi.org/10.5194/esd-13-1377-2022.

Soci, C., Hersbach, H., Simmons, A., Poli, P., Bell, B., Berrisford, P., ... & Thépaut, J. N. (2024). The ERA5 global reanalysis from 1940 to 2022. *Quarterly Journal of the Royal Meteorological Society*, *150*(764), 4014-4048.

Sodoge, J., Kuhlicke, C., Mahecha, M. D., & de Brito, M. M. (2024). Text mining uncovers the unique dynamics of socio-economic impacts of the 2018–2022 multi-year drought in Germany. *Natural Hazards and Earth System Sciences*, *24*(5), 1757-1777.

Thiery, W., Lange, S., Rogelj, J., Schleussner, C. F., Gudmundsson, L., Seneviratne, S. I., ... & Wada, Y. (2021). Intergenerational inequities in exposure to climate extremes. *Science*, *374*(6564), 158-160.

Taniushkina, D., Lukashevich, A., Shevchenko, V., Belalov, I. S., Sotiriadi, N., Narozhnaia, V., ... & Maximov, Y. (2024). Case study on climate change effects and food security in Southeast Asia. *Scientific Reports*, *14*(1), 16150.

United Republic of Tanzania (2022). National Disaster Management Strategy 2022 – 2027. Prime Minister's Office, Disaster Management Division. Accessed at: https://www.pmo.go.tz/uploads/documents/sw-1677564328-National%20Disaster%20Management%20Strategy%202022%20%E2%80%93%202027.pdf on 02-07-2025

Wang, N., Sun, F., Yang, S. *et al.* Flood fatalities and displacement influence human migration in floodplains of developing countries. *Commun Earth Environ* **6**, 319 (2025). https://doi.org/10.1038/s43247-025-02293-2

460 WEF: World Economic Forum (2025). Global Risks Report 2025. Accessed at: https://reports.weforum.org/docs/WEF_Global_Risks_Report_2025.pdf on 02-07-2025

WMO, 2023. Atlas of Mortality and Economic Losses from Weather, Climate and Water-related Hazards (1970-2021). WMO-No. 1267. Accessed at: https://wmo.int/publication-series/atlas-of-mortality-and-economic-losses-from-weather-climate-and-465 water-related-hazards-1970-2021 on 02-07-2025

Zhao, L., Oleson, K., Bou-Zeid, E., Krayenhoff, E. S., Bray, A., Zhu, Q., ... & Oppenheimer, M. (2021). Global multi-model projections of local urban climates. Nature Climate Change, 11(2), 152-157.