

## Reviewer #1

*The authors provide a nice framework by identifying three core challenges: impact data, impact genesis, and impact projection. The discussion of recent advances like LLMs, storyline projections, and high-resolution datasets is valuable. The manuscript is well-written, interdisciplinary, and robustly supported by literature.*

We thank the Reviewer for their constructive comments and positive outlook on our paper. We provide below replies to the specific comments, detailing the edits that we have implemented in the revised version of our manuscript.

*Here are some points to further enhance the paper's contribution:*

- 1. Section 3.1 (LLMs for Impact Data): The application of new techniques, e.g., LLMs, is promising. I recommend adding a clear statement on the necessity of careful calibration and validation to ensure the reliability of these methods and prevent significant errors.*

We fully agree. We have rephrased ll. 155-158 as follows: “The automated analysis of textual sources comes with both technical challenges and limitations in data quality. Any automated approach, including LLMs, 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.”

- 2. Section 3.2 (Impact Genesis): The opportunities discussed do not fully address the challenge mentioned before, especially, quantifying indirect and cascading impacts. This topic can be expanded by at least including some practices, e.g., Colon et al., 2021, where the indirect economic loss caused by flood via supply-chain is quantified using agent-based modelling, to give a better perspective.*

We partly disagree, as both the contribution from the social sciences and the analysis of intersecting vulnerabilities directly inform on the genesis of impacts, and the former can address cascading impacts, as evidenced by Rusca et al. (2021). We nonetheless recognise that agent-based models such as that developed by Colon et al. (2021), also provide a powerful tool to advance understanding of impact genesis. We have integrated them in the discussion on ll. 173 and following: “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).”

- 3. Section 3.3 (Impact Projection): Including the "reversal of the impact chain" framework (Pfleiderer et al., 2025) would strengthen the discussion on uncertainty control and provide a valuable perspective for generating actionable climate information.*

This is a good suggestion, that we have included in our text. We have updated ll. 201 and following: “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).”

4. *Event Typology: The discussion would benefit from considering high-impact events driven by spatial concurrence or temporal recurrence, not just statistical extremity. This is a critical dimension of comprehensive risk assessment.*

Please see our answer to point 5 below. We also highlight that non-extreme events can cause large impacts on ll. 247–249: “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).”

5. *Sectoral Scope: Expanding the scope of the cases beyond health and hydrology to include key sectors like agriculture, infrastructure, and human security (e.g., displacement) would significantly increase the paper's relevance for a broader audience of stakeholders.*

Following the Reviewer’s comment #4, we have clarified on ll. 99 and following that, high-impact events are not necessarily extreme in the statistical sense of the meaning. As part of this edit, we have added an example from the agricultural sector of impacts resulting from compound events that were not individually extreme: “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.”

We already present an example of infrastructure-related impacts (the management of the Wivenhoe Dam in Brisbane in Sect. 2.2). To further broaden the appeal of our text, we now explicitly refer to human displacement in conjunction with the mention of analyses based on nightlight data on ll. 159 and following: “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).”

6. *Equality Dimension: The paper can more explicitly discuss how structural inequalities (e.g., based on gender, income) fundamentally shape exposure and adaptive capacity, moving beyond an acknowledgment of differential vulnerability.*

This perspective is at the core of the socio-environmental storylines and sociohydrology approaches that we describe in the paper. We have clarified this on ll. 178 and following: “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.”

We moreover clarify that the example provided on II. 95 and following can be viewed as resulting from structural inequality: “Moreover, the aggregated impacts for a given event often conceal how structural inequalities and pre-existing vulnerabilities shape differential impacts across populations.”

Ben-Ari, T., Boé, J., Ciais, P., Lecerf, R., Van der Velde, M., and Makowski, D.: Causes and implications of the unforeseen 2016 extreme yield loss in the breadbasket of France, *Nat. Commun.*, 9, 1627, <https://doi.org/10.1038/s41467-018-04087-x>, 2018.

Colon, C., Hallegatte, S. & Rozenberg, J. Criticality analysis of a country’s transport network via an agent-based supply chain model. *Nat Sustain* 4, 209–215 (2021). <https://doi.org/10.1038/s41893-020-00649-4>

Enenkel, M., Shrestha, R.M., Stokes, E., Roman, M., Wang, Z., Espinosa, M.T.M., Hajzmanova, I., Ginnetti, J., Vinck, P., 2020. Emergencies do not stop at night: Advanced analysis of displacement based on satellite-derived nighttime light observations. *IBM J. Res. & Dev.* 766 64, 8:1-8:12. <https://doi.org/10.1147/JRD.2019.2954404>

Leonard, M., Westra, S., Phatak, A., Lambert, M., van den Hurk, B., McInnes, K., ... & Stafford-Smith, M. (2014). A compound event framework for understanding extreme impacts. *Wiley Interdisciplinary Reviews: Climate Change*, 5(1), 113-128.

Lindersson, S., Raffetti, E., Rusca, M. et al. The wider the gap between rich and poor the higher the flood mortality. *Nat Sustain* 6, 995–1005 (2023). <https://doi.org/10.1038/s41893-023-01107-7>

Mazzoleni, M., Mondino, E., Matanó, A., Van Loon, A. F., & Barendrecht, M. H. (2024). Modelling the role of multiple risk attitudes in implementing adaptation measures to reduce drought and flood losses. *Journal of Hydrology*, 636, 131305.

Pfleiderer, P., Jézéquel, A., Legrand, J., Legrix, N., Markantonis, I., Vignotto, E., and Yiou, P.: Simulating compound weather extremes responsible for critical crop failure with stochastic weather generators, *Earth Syst. Dynam.*, 12, 103–120, <https://doi.org/10.5194/esd-12-103-2021>, 2021.

Pfleiderer, P., Frölicher, T.L., Kropf, C.M. et al. Reversal of the impact chain for actionable climate information. *Nat. Geosci.* 18, 10–19 (2025). <https://doi.org/10.1038/s41561-024-01597-w>

## Reviewer #2

*This article discusses the importance of better understanding how societies around the world are increasingly impacted by climate extremes. The paper is topically relevant for ESD. It does not present novel tools or data, but instead highlights that there is both a need for more progress on impact modeling and a good potential to do so. The paper does not reach substantial new conclusions, as it is more of a position paper than a research paper.*

We thank the Reviewer for their constructive comments. We underscore that we submitted this paper as a Perspective and not as a Research Article. We thus had as aim to write a position paper. We provide below replies to the specific comments, detailing the edits that we have implemented in the revised version of our manuscript.

*My feeling is that the paper can serve a valuable purpose by helping to draw attention to the relatively primitive state of impact modelling, and by raising some interesting ideas for progress such as the use of LLMs. However I think it can be improved to do a stronger job of this, and could also connect better to a wider swath of relevant literature. I'd therefore suggest a substantial revision, and am providing some suggestions that will hopefully contribute to this.*

*As one over-arching comment, I think the article could provide more conceptual detail regarding the challenge of understanding impacts, which are fundamentally coupled human-Earth system phenomena and therefore require both natural and human processes. To my (perhaps simplistic) way of thinking, the essential aspects that need to be resolved on the human side are:*

*1. spatial details of the technosphere, including the aspects of the built environment that are vulnerable and/or modify the impacts resulting from extreme climates. For example, the roadways and transportation hubs that could be affected by floods, the electrical systems that could fail under heavy loading, or the low-lying houses that could be inundated by sea level rise (e.g. Willard-Stepan, 2025), or the air-conditioning systems that mitigate heat waves.*

*2. the spatial details of human populations themselves, and their activities. There is work on spatially-detailed exposure to heat stress, for example (e.g. Dunne, Nature Climate Change 2013; Vecellio, PNAS 2023), but this could be expanded to other variables.*

*Both of these aspects could easily become overwhelmingly complicated, but I think it's feasible that useful levels of detail could be developed, at which impact risks become reasonably resolved. I am not advocating that the authors necessarily add discussion of these two aspects, but am offering them as an example in trying to spur more mechanistic conceptual discussion.*

The first point raised by the Reviewer echoes one of the comments from the other Reviewer. We recognise the key importance of the human dimension, including the built environment and other aspects of the technosphere/anthroposphere, and propose to integrate a discussion of this throughout the paper, highlighting concrete examples. Specific implemented textual edits are:

II. 30 and following: "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."

II. 85 and following: "The impacts of a climate extreme often arise from complex interactions between biophysical, technological and societal factors"

II. 92 and following: “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.”

II. 198 and following: “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).”

II. 250 and following: “A holistic understanding of the multifaceted impacts of climate extremes, of the biophysical, technological and societal processes shaping their impacts, and of potential future impacts, are valuable tools to ensure just and resilient societies in the face of a changing climate.”

Concerning the second point, we view this to some extent as a specific facet of the human dimension. We have added the following explicit mentions of the role of human activities and societal and individual characteristics, including an example drawn from a paper on adaptation to heatwaves in line with the papers suggested by the Reviewer:

II. 89 and following: “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).”

II. 133 and following: “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”.

*More detailed points for consideration:*

*1. It may be useful to provide a definition of what an ‘impact’ is, as well as some kind of taxonomy of impacts. Personally I found the distinction between hazard and impact useful - perhaps this could be highlighted a bit more up front, even in the abstract? In terms of a potential taxonomy, it seemed the authors are mostly thinking about heat waves, droughts and rain-driven floods, but there could be many other impact types such as long-term sea level rise, fires, or changes in ecosystem function. There are also systemic effects, such as economic disruption, in addition to the local acute impacts. Some kind of structured list might provide a novel resource to help to expand peoples’ thinking on the world of impacts, and help to spur new research lines.*

We are glad to hear that the Reviewer found this distinction helpful, and we believe that the literature would benefit for a more precise use of the terms “hazard” and “impact”. We have implemented the changes below to clarify this distinction throughout the text and provide further insights on the distinction. We however refrain from providing a complete taxonomy, as this would be a perspective paper of its own (one such paper was for example written by Jakob Zscheischler and colleagues to provide a taxonomy of compound climate events).

Il. 27 and following: “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).”

Il. 40 and following: “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).”

Il. 115 and following: “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; González-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) ...”

Il. 247 and following: “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.”

*2. I think it would be helpful to emphasize more prominently - especially in the introduction - the fact that impacts sit on the boundary of natural and social science, and therefore have been chronically understudied: they do not easily fit into disciplines. Impact projections require simultaneously projecting the natural climate change and the societal change. There are a number of papers talking about this issue, with respect to the gap between human systems and climate models, such as work by Beckage (e.g. Climatic Change, 2020) and Tapiador (Environmental Research Climate, 2024).*

The Reviewer makes a valid point. While we highlight the relevance of jointly considering both natural and human systems at various points in the paper – for example in Sect. 2.2 and in Sect. 3.3 when discussing storylines – we recognise that it is given less prominence in the introductory part of the paper. We further recognise that we missed highlighting recent proposals for integration of human dynamics in Earth System models. We have implemented the following edits to address this:

Il. 30 and following: “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.” (see also our reply to point 5 below)

Il. 40 and following: “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).”

Il. 212 and following: “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.”

We additionally highlight the positioning of work on impacts of climate extremes at the interface of the natural and social sciences on ll. 223 and following: “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.”

*3. The figure forms a central part of the paper, but I found it difficult to understand what was intended by the first two categories. Data is always a challenge in every branch of science, and ‘genesis’ implies a beginning - it’s not clear if this would apply to the beginning of the social structure that led to vulnerability, or what. I would suggest that the authors consider renaming these as ‘Observational challenge’ for the first, and ‘Process understanding challenge’ for the second, as I think these terms may more accurately express what the authors intend to convey?*

We disagree with the Reviewer’s statement that data is always a challenge. As example, one of the authors of this submission has worked for several years on applying dynamical systems theory to climate datasets. The challenges there have been primarily of a mathematical and technical nature, while data availability has not been a major hinder. Moreover, for impacts it is not only observational data that is limited, but also modelling data. We thus do not feel that the suggested renaming would reflect the challenges in the data realm.

We instead agree with the suggestion to review the term “genesis”, and have update the figure and the corresponding text to use “process understanding” instead. This indeed reflects better the challenges that we outline in Sect. 2.2.

*4. Section 3.3 talks a lot about storylines, which can be good for expanding imagination. Yet storylines, on their own, do not make use of physical principles that can constrain the realm of what is actually feasible or likely. I think it’s important to develop mechanistic models, based on physical foundations, that can help point towards the likely outcomes of actions. If the authors agree, it would be good to emphasize that storylines are not enough.*

We clarify that the storyline approaches we present combine quantitative information from numerical climate projections with qualitative information on societal processes. We would therefore argue that they do to some extent focus on the realm of what is possible and plausible, although as the Reviewer correctly notes they cannot be used to quantify likelihood.

Upon rereading our text, we however recognise that the incipit of Sect. 3.3 may have appeared too critical of process-based models. We therefore now state clearly that improvements in such models are a necessary part of the toolbox to better project the impacts of climate extremes.

Specifically, we have updated the text on ll. 188 and following to: “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."

We have also included additional edits in the text in view of the Reviewer's comment #5.

*5. Any impact assessment is always going to be inherently probabilistic, rather than deterministic. So presumably the goal is not to predict events, but to map out types of events that are more likely to occur. These will be most useful if society can use them to pre-emptively adjust, altering the technosphere or human behaviour. I think this fact makes it especially important to resolve both the technosphere and human behaviour within the impact assessment framework - not because they can be predicted in any deterministic sense, but because these are the variables that can be adjusted, so understanding how they fit into the evolution of risk is very valuable.*

We fully agree with the point the Reviewer is making regarding the importance of integrating the human dimension, including the anthroposphere/technosphere, in impact assessment frameworks. Indeed, this is what motivated our focus on storylines in Sect. 3.3, as we view them as a powerful tool to implement in practice such integration. We refer the Reviewer to the updated text included in our replies to their comments #2 and #4 for the specific edits that we have implemented, which span the full length of the paper.

Ahmed, I., van Esch, M., & van der Hoeven, F. (2025). Behavioural adaptation to heatwaves in a temperate city: Insights from Rotterdam. *Cities*, 165(10616).

González-Abad, J., & Gutiérrez, J. M. (2025). Are deep learning methods suitable for downscaling global climate projections? An intercomparison for temperature and precipitation over Spain. *Artificial Intelligence for the Earth Systems*, 4(4), 240121.

Goulart, H. M., Athanasiou, P., van Ginkel, K., van der Wiel, K., Winter, G., Pinto, I., & van den Hurk, B. (2025). Exploring coastal climate adaptation through storylines: Insights from cyclone Idai in Beira, Mozambique. *Cell Reports Sustainability*, 2(1).

Tapiador, F. J., & Navarro, A. (2024). Coupling human dynamics with the physics of climate: a path towards Human Earth Systems Models. *Environmental Research: Climate*, 3(4), 043001.

Van Der Geest, K., & Van Den Berg, R. (2021). Slow-onset events: a review of the evidence from the IPCC Special Reports on Land, Oceans and Cryosphere. *Current Opinion in Environmental Sustainability*, 50, 109-120.