Reply to reviewers

We would like to thank the reviewers for valuable suggestions and comments. We reply to each of these with page number and line indications based on the clean manuscript (no track changes). **P** refers to the page number and **L** refers to the line number. For example, **P3L65-70**, refers to page 3, lines 65-70.

Reviewer 1		
No	**Comment**	**Reply**
1	This article is in line with the current research on climate risks, which builds on the single hazard perspective to work with a multi-hazard perspective. This work is very interesting and a very valuable contribution to the current research on climate risks. It builds on theme of multi-hazards, expanding the knowledge on compound and cascading drought and heatwave risks, with also a novelty in the approach, using machine learning. The article is well written and easy to read. The structure of the article is also coherent and easy to follow.	We would like to thank the referee for the acknowledgement of the novelty of our paper, contributing to the current research on climate risk and multi hazard framework.
2	Introduction: from my perspective the introduction is interesting and includes many good references but lacks references from a "higher-level perspective". I would suggest to includes references to the most recent reports of the IPCC, IPBES or the European climate risks assessment report (European Climate Risk Assessment | European Environment Agency's home page).	In our manuscript, we cited IPCC AR6 report, which is the latest IPCC report. However, we would like to acknowledge the authors of working group 1 where the text was cited. Thus, we cited the IPCC report as Seneviratne et al. (2021) instead of IPCC (2021). EEA (2024) and IPBES (2021) references have been added in the revised version (**P2L26**).
3	More information about machine-learning: I suggest including more discussion on the advantages and drawbacks of using machine-learning versus other methodologies/tools. This discussion could be part of section 4 or 5 but it could also be part of the Introduction, for example, in the third paragraph. What tools were used before to do this kind of estimate? Why do we need ML? What are the advantages? What are the drawbacks? Can we validate the results? How? It is already partly covered in the article but I think it would be further discussed.	We thank the reviewer for his/her valuable suggestions. We expanded the introduction section, explaining the machine learning approach used in Stagge et al. (2015), Bachmari et al. (2017), and Sutanto et al. (2019a) (**P2L54-P3L61**). We discussed the advantages and disadvantages of ML approach, such as offering direct impact prediction and required robust impact data in the discussion section, paragraph 2 and 3 (**P16L358-378**).
4	In Section 2: The definition of cascading events is not very clear to me. This part of the section needs more explanation, maybe not a detailed description like in the previous articles you mentioned, but a more detailed description is important as this is a central part of the article.	The definition of compound and cascading events employed in this study was expanded in the Section 2.4 (**P5L137-150**). In addition, Table 1 showing examples of compound and cascading events was added so readers can understand the definition easily (**P6**).
5	Section 3.3: When you summarize the results in the table, it would also be good to say how these results compare to the results from existing literature and	Suggestion is accepted. We compared our findings with previous literature on drought, heatwave, and compound projection literature. In general, our findings align with studies from Samaniego et al. (2018) who

	potentially comment if there are differences.	found that EE and SE will experience higher and longer droughts (**P12L264-265**). Similarly, our heatwave findings are in agreement with a study conducted by Fischer and Schär (2010) and Lin et al. (2022) for SE, EE, and WE. However, we did not project that NE will experience high heatwave as it is found in Lin et al. (2022) (**P13L277-285**). For CDH results, we confirmed the findings with literature conducted by Mekherjee and Mishra (2021) and Tripathy et al. (2023) (**P13L296-298**).
6	Description of the scenario: I might have missed it, but I don't think I found a description of the scenarios RCP-SSP. It does not need to be long, but it might be good to briefly describe what these scenarios mean. It could be in section 2 for example.	The reviewer is correct. We overlooked the climate scenarios since we assumed the readers are familiar with this. We added information of SSP scenarios in Section 2.1 (**P3L82-83**).
7	Line 19: I think a word might be missing here, when you say "economic, non-economic and ecosystem". Economic impacts? Sectors? I would recommend reformulating this sentence.	We thank the reviewer for careful reading. We agree that the sentence misses the word sectors. We revised the sentence accordingly (**P1L20**).
8	Line 22: "urgency of climate mitigation". Climate adaptation could also be mentioned here.	We revised the sentence into: "…urgency of climate adaptation and mitigation…" (**P1L22**).
9	The concluding section is quite short, I wish it would include a few recommendations for the future. What data do you need to make your work adaptable to Europe in general? Outside Europe? It is complementary to other technics/tools/methods? Can this information be used by decision makers? If yes, how? In which context?	The conclusion is short because we would like to make it concise by only describing the main findings of our study. However, we agree, and we added one paragraph about recommendation. Thus section 5 became conclusion and recommendation section. Information regarding the applicability of our approach to outside Europe was added. We also suggest for the establishment of a standardized, global multi-hazard impact database to support improved ML model development for drought and heatwave impact-based forecasting. We also recommend to integrate CnC risk assessments into national and regional climate adaptation and disaster risk reduction strategies. Furthermore, we suggest that regional planning should move beyond historically identified hotspots and address emerging risk zones, especially in southern and central Europe, where both hazard characteristics are projected to increase (**P18L416-423**).
10	Figure • Modifying the colormap could be good, there might be other colormaps to use where it is easier to see the positive vs negative differences.	We modified the colormap in the revised version to improve its readable. Moreover, the sub-titles have been added. The plotting boundaries, right and bottom, have been cut, thus removing the white areas outside the study regions.

	• I would suggest including sub-titles for the different panels when you have several figures so the reader doesn't have to look at the legend every time. Is it possible to fit the figures where you have results? There are white areas on the right sides of figures and down which are usually removed.	

References

Seneviratne, S. I., Zhang, X., Adnan, M., Badi, W., Dereczynski, C., and co authors: Weather and Climate Extreme Events in a Changing Climate. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1513–1766, https://doi.org/https://doi.org/10.1017/9781009157896.013, 2021.

Reviewer 2		
No	**Comment**	**Reply**
1	This constitutes an interesting study, however I do have some concerns regarding the downscaling procedures applied. Further, the authors should look spend more time in investigating the model skill of used ISIMIP data compared to ERA5. Additional comments relate to the impact projections which are provided in units of time not damage. The paper should also be proofread again, to remove a few remaining grammatical errors.	We thank the referee for his/her positive interest in our study, and support in improving our manuscript. Regarding the downscaling, we employed the bilinear interpolation approach on the ISIMIP datasets. We did not apply statistical or dynamical downscaling techniques, and as such the resampling of the ISIMIP data did not substantially change the climate change signal that is contained in these data (**P3L84-P4L90**). To avoid any further confusion, we renamed the downscaling into resampling. Our study does not aim to evaluate the performance of ISIMIP models compared to ERA5. However, we utilized ERA5 Land soil moisture data for bias corrected the soil moisture data simulated by CWAT model forced with ISIMIP climate models (**P3L83-84**). This approach is commonly used in many studies dealing with climate change datasets. Employing the machine learning approach to predict drought and heatwave impacts will result, in general, likelihood of impact occurrences (LIO) as presented by previous studies (e.g., Stagge et al., 2015; Blauhut et al., 2015; Bachmair et al., 2017; Sutanto et al., 2019a). The machine learning approach utilized in this study only uses binary time series of impact occurrences, yes or no impact (**P2L54-P3L59**). Furthermore, we combined impact data from different sectors due to data limitation. By doing this, no damage can be predicted. We suggest that impact database should provide detailed reported damage. If the damage data becomes available, future study could utilize this dataset for damage predictions (**P18L423-425**). We added this information in the introduction and recommendation sections in the revised version.
2	l.3-4 Not clear what this sentence is trying to say	We have rewritten the sentence into: "Yet, most studies on drought and heatwave have focused on single hazard events rather than compound and cascading events and their potential impacts" (**P1L3-4**).
3	l.14 wrong grammar 'in the west europe'	It is now written as "in western Europe" (**P1L14**).
4	l.35 it should be defined what the authors consider compound and cascading hazards. Are these temporally concurrent events or sequential events or both? The term 'cascading' implies a causal relationship between both events (i.e. a trigger –	We thank the reviewer for the suggestion. The definition of compound and cascading events was mentioned in the first paragraph. We define compound event if drought and heatwave occurred at the same time and place (concurrent) and cascading event if

	response dynamic) and should not be used if event relationships are investigated stochastically, only.	drought and heatwave occurred one after another at the same time and place (sequential) (**P2L26-28**). Furthermore, we explained the definitions in a more detailed manner in the section 2.4. These definitions have been applied in previous studies (Leonard et al., 2014; Liu and Huang, 2015; Vitolo et al., 2019; Sutanto et al., 2019) (**P5L137-141**).
5	l.55 agricultural droughts and hydrological droughts are different things, I would suggest to just use 'drought' here defined by soil moisture deficiency.	We used the term hydrological drought and removed the word agriculture (**P3L62-63**). Soil moisture is one of the hydrological components and therefore, we prefer to identify soil moisture drought as hydrological drought instead of agricultural drought.
6	l.58 – 61 as mentioned above I would suggest to stick with the compound event typology described in Zscheischler et al. 2021 and elsewhere by refereeing to these two event types as temporally compounding (consecutive events over same place) and spatially compounding event (concurrent events over same place).	We understand that some studies used the term compound event only to indicate both the events that are concurrent and simultaneous. However, we prefer to split this definition into two: compound and cascading. If drought occurs after heatwave event is over (here the temperature back to normal-high, not extreme), then we define this event as cascading and not compound/concurrent because there is only one single hazard left in the end (see point 4). We further clarified this definition in the method section (**P5L137-141**). Reference Zscheischler et al. (2020) was added.
7	l.77 downscaling the low. Res. data (drought) instead of upscaling the high. Res. data, gives a wrong sense of accuracy. Results should be investigated at the lowest resolution available.	We thank the reviewer for the feedback. The rationale behind the downscaling (will be resampling) soil moisture and temperature data is to achieve high resolution results, which is needed for sectoral applications. Figure 1 below shows the difference between results using ISIMIP resolution (100 km) and ERA5 Land resolution (10 km). It is obvious that high resolution data will have better impression for discussing about natural hazard impacts with stakeholders. Moreover, we aim to use drought and heatwave indices to develop impact prediction algorithms using machine learning and impact data at the national level. Using a coarse resolution for impact prediction will result in limited number of grid cells. We described this in the method section (**P3L86-88**).
8	l.99 sentence seems wrong: 'wrong data mined (?).. '	We revised the word to "data mining" (**P4L112**).
9	l.124. split sentence, it is hard to understand.	We split the sentence into "To analyse the CnC events, binary maps consist of the number 1 for heatwave and 2 for drought were generated if the month is identified as drought or heatwave month. For no hazard month, 0 value is applied" (**P5L142-143**).
10	Figures 1-4 how do ISIMIP models perform against ERA5 for drought / heatwaves and compound events over the historical	In this study, we did not evaluate the performance of ISIMIP models for identifying drought and heatwave characteristics compared to ERA5. The goal of our study is to

	period? This deserves a paragraph and at least some figures in the SI.	analyze the changes in drought and heatwave characteristics including their compounding events in a warming world. Some previous studies also utilized the ERA5 datasets for downscaling and bias corrected ISIMIP model. We suggest that future study may focus on the performance of ISIMIP models in identifying drought and heatwave compared to ERA5.
11	Figures: please don't use rainbow color scales, see link for reasons: https://blogs.egu.eu/divisions/gd/2017/08/23/the-rainbow-colour-map/	We revised the colormap as it is also suggested by reviewer 1.
12	Table / Figure 5: Where are these Regions? This should be marked in the Figures 1-4 or an additional figure with defined regions should be provided in the SI.	The regions are presented in the Supplementary Figure S9. We mentioned this in **P11L260-261**.
13	l.257 'What is more' is not a usual expression.	I think the reviewer means L275. We revised the word into "furthermore" (**P13L304**).
14	l.283 "For heatwaves, the model evaluation shows a perfect score (AUC=1), which may be influenced by the limited amount of reported impact data (Supplementary Fig. S10d)." This seems odd, how can a small sample size lead to a perfect model performance? Please explain.	We thank for the valuable feedback. The AUC can generate a value 1 when the sample size is small. First, the AUC measures the ability of a classifier to rank a randomly chosen positive instance higher than a randomly chosen negative one. If we have 2 positive and 2 negative samples and the model predicts these correctly by "accident" then the AUC will be 1 although it is not statistically robust. Second, with a small sample, there is an overfitting risk. With very small datasets, models can memorize the training data instead of learning generalizable patterns. This overfitting can lead to perfect discrimination. We explained this issue in the revised version (**P14L313-315**).
15	Results in Fig. 6 I don't understand why impacts are provided in units of time. Impacts should be measured as monetary damage e.g. in currency (econ. Impacts), or excess mortality (health impacts). The y-axis units in Figure six are not provided and 'Number of Impact' is probably Grammarly wrong.	As explained in point 1, the machine learning approach utilized in this study only uses binary time series of impact occurrences, yes (1) or no impact (0). The reported impact database such as EDII does not provide detailed economic damage per sector so we could not predict the damage. If the damage data becomes available, future study could utilize this dataset for damage predictions. The Y axis shows the occurrence of impact in a year when impacts are predicted from all models.
16	l.377 this is an overstatement. There are numerous studies on compound drought and heat occurrences, which should be cited here. A simple search in google scholar will reveal numerous papers.	We are not sure, which sentence that the reviewer referring to. L377 is "We projected that drought impacts on economic, non-economic, and ecosystem sectors in Germany will be double in 2100, while heatwave impacts on human health and mortality will increase ninefold." In this sentence, we refer to drought and heatwave impacts and not events. In addition, previous studies on drought and heatwave events in Europe

		support our findings that both events will increase due to climate change.