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## **Comment on nhess-2022-18**

Marthe Wens (Referee)

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Referee comment on "Evolution of multivariate drought hazard, vulnerability and risk in India under climate change" by Venkataswamy Sahana and Arpita Mondal, Nat. Hazards Earth Syst. Sci. Discuss., <https://doi.org/10.5194/nhess-2022-18-RC1>, 2022

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Dear authors

I have read your manuscript and think it covers an interesting topic. It is clearly the result of a major research effort. Including vulnerability in drought risk analysis is a known challenge, and I agree with you that looking at multiple physical drivers as well as at transient vulnerability are important steps for holistic drought risk assessments. The aim of the study is clearly stated and results are described in detail. However, the research is quite complex and so I think an extra effort is needed to make it understandable for readers of NHESS. I see some conceptual issues, but they may have been caused by a lack of understanding of the method due to its incomplete or undetailed description. In general, I think more of the method could be in the main manuscript and more details to the method (currently lacking) can be described in the supplementary material. Below, I will elaborate on the main points that I think can help improve/clarify the manuscript. In addition, I think the manuscript would benefit from a review by an English language editor, as there are multiple grammar mistakes in the manuscript and I see various possibilities for vocabulary improvements.

I haven't listed all grammar / vocabulary mistakes, but here are a few examples from the abstract:

e.g. L7 "a" major threat

e.g. L10 This study investigates and evaluates the change in projected drought risk under future climatic and socio-economic conditions by combining vulnerability and hazard information at a country-wide scale for future climatic and socio-economic conditions

e.g. L18 "are found to be high risk under all scenarios"

e.g. L15-17: Sentence is too long, it is unclear what is meant with "worst-case" scenario, I think maybe "The West Uttar Pradesh, Haryana, ..., regions" are meant rather than "regions of West Uttar Pradesh,..."

In general, in the manuscript there are many sentences that are difficult to understand (too long and/or with too complex structure).

Below, I add some general comments and questions structured following the study aims, highlighting the most pressing questions with respect to the method.

### **1. Multivariate drought hazard projection using Multivariate Standardized Drought Index (MSDI) that considers concurrent deficits in precipitation and soil moisture for future warming scenarios**

L81: "However, droughts can often manifest as a complex interplay of multiple influencing variables necessitating a multivariate approach for characterization of drought hazard (Sahana et al., 2020). For the agrarian country of India, agro-meteorological drought hazard projections should consider deficits in precipitation or soil moisture or both" I agree looking only at PR is too narrow. It is indeed interesting to look at both, but as far as I understand the method, only events with both a SM-deficit and a PR-deficit are considered. Is this approach justified? I can think of cases where a SM-deficit alone is enough to cause a drought impact – I feel the hazard method does not sufficiently take into account the propagation of drought through the hydrological cycle, which involves attenuation and lag effects. The manuscript displays different results than other papers: how can it be evidenced that the presented method is better and the results are more reliable than those of other studies?

L81: "The above two datasets are regridded to a common spatial resolution of  $0.5^\circ$  lat.  $\times$   $0.5^\circ$  lon. and rescaled to monthly frequencies for the historical drought hazard assessment." Could you please explain in the supplementary material how this is done? Is there an increased spatial variability included by this re-gridding to counteract an averaging effect?

L75 + 83: "The drought hazard assessment for baseline period (1980-2015) requires observed hydroclimatic variables" + "In order to evaluate the projected drought hazard over India, the projected precipitation and soil moisture data at a spatial resolution of  $0.5^\circ \text{ lat.} \times 0.5^\circ \text{ lon.}$  is obtained from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) (Warszawski et al., 2014). The historical (1980-2005) and projected (2006-2099) data from available GCMs namely ...." How did you deal with the overlapping time period between observed and modelling data? Was, for example, the Delta Method (projecting the difference between modelled historic and projected onto the observed data; or; projecting to difference between observed and modelled historic onto the projected data) applied? I do not find information on how the final hazard dataset is constructed – so I suggest adding this to the supplementary material. It would be nice to show with some figures how the ISIMIP data and the used observed IMD Pr and MERRA SM data compare?

L93 "The spatial pattern of annual mean surface soil moisture for India from the LPJmL impact model is consistent with the satellite-based Essential Climate Variable soil moisture product (Gu et al., 2019)." Is this ECV similar to the MERRA Land data used? Or how is it connected to the data used?

L95 "Although the simulated soil moisture data underestimates the monsoon months' soil moisture (June, Jul, Aug, Sep) during the historic period (1980-2005), we did not perform the bias correction, since we intend to capture the variability in the soil moisture rather than their magnitudes for drought index calculation" – can you please add graphs / maps to show this in the supplementary please?

In the Supplementary Material (drought hazard assessment and S1): Is the co-occurrence – covariance of Pr and SM modelled per ensemble member after which the mean of the DH value is calculated? Or are ensemble mean / median PR and SM used to calculate the DH value? What are  $r_k$  and  $s_k$  in formula 2 – are they thresholds for droughts in SM and PR?

In the Supplementary Material (drought hazard assessment): Until "The MSDI series at each region is categorized into four groups similar to Mckee et al. (1993)." I could follow the description, then it becomes unclear – please add more detail (e.g., on the weighing and rating: I do not understand why nor how this is done) and please add some examples to showcase and justify the method.

Supplementary "Further, each category is organised into sub-groups based on the occurrence probabilities of the selected category. While the weightages are assigned to MSDI categories to account for drought magnitude, ratings are assigned to the sub-groups of each MSDI category to account for drought occurrence probability." -> which categories? And how does dividing based on occurrence probabilities differ from McKee et al? That is what they do, too, no? I do not understand why both are needed since they (intensity and probability) are intrinsically linked.

## **2. Drought vulnerability 65 projection considering combinations of RCP and SSP scenarios, using a list of drought vulnerability indicators that represent exposure, sensitivity and adaptive capacity components.**

The manuscripts' understanding of vulnerability (including exposure) does not fully match the understanding of this concept by the sources cited (IPCC AR5) and does not match L36 (although it is true other authors see exposure as part of vulnerability – so I suggest look up other scholars who also include exposure as part of the vulnerability quantification). Besides, with respect to the chosen vulnerability factors, I think multiple interesting other social, economic vulnerability indicators could have been selected (e.g., Meza et al 2020 <https://nhess.copernicus.org/articles/20/695/2020/> )

Table 1: I do not always follow the reasoning regarding the relevance (I would not say population density and land use cover are proxies for social vulnerability) but more importantly: I would like to see some more information about how these indices are calculated (population density is pop sum / area; but how is the water bodies fraction calculated, or the irrigation index? How does the water holding capacity positively influence the vulnerability?). Besides, I see different sources used to the observed versus projected situation: how is consistency ensured?

In the supplementary material: Please repeat the weights of Thomas and Sahana for the vulnerability indicators

## **3. Drought risk projection integrating hazard and drought vulnerability information.**

In general, there is no validation of the presented risk approach since the past risk analysis (1980-2015) is not compared with observed risk / reported impacts. This should be done in order to give credibility to the method, or – if impossible – be addressed in the discussion section.

L119 *"Drought risk values computed using Eq 1 are further standardized to obtain the Drought Risk Index (DRI)."* Can you please elaborate how this is done? Two standardized indices are multiplied so I do not see the need to standardize the result again – this introduces some loss of information ?

The effect of climate change is taken into account in two ways: by changing vulnerability (multiple vulnerability indicators are based on average water availability) and by changing hazard occurrence. I think this is interesting but it is a pity that social vulnerability factors, influenced by socio-economic development, are not taken into account – this might have

changed the vulnerability trend hence risk trend. Would it be possible to account for this?

The classification of very low to very high and transition plots are interesting but it is unclear how these classes are defined. Moreover, there are regions with a very high historic hazard that change to low hazard – this is remarkable since this is not immediately clear from the average SM - PR maps in figure S2. Can you please explain this difference?

Fig2: I do not understand why land cover changes based on RCPs? Shouldn't this be SSP? Besides, I wonder why baseline (1980-2015) isn't shown? Now it is indicated as "2010" but that seems inconsistent with the method section.

#### **4. Development of bivariate choropleth plots under future scenarios to quantify the individual roles of climate and societal changes in driving drought risk**

This is a good way of visualising the results; but I would suggest to change the colour classes since now on e.g., the RCP6.0 near future, barely any variance is visible.

#### **5. Identification of regions and zones that are expected to be under worst drought risk conditions in the near and far future**

(Make sure that in the discussion, the results are compared with papers who have a similar conception of vulnerability – or discuss the difference – because that might also be the cause of the diverging results)

Respectfully