Cover Letter

February 20, 2024

Dear Editor,

We would like to thank you, the associate editor and the anonymous reviewers for constructive comments and suggestions, which have significantly improved our manuscript (**hess-2023-181**).

Climate change accelerates the water cycle, thus complicating the projection of future streamflow and hydrological droughts. Although machine learning is increasingly employed for hydrological simulations, few studies have used it to project hydrological droughts, not to mention the bivariate risks of drought duration and severity as well as their socioeconomic implications under climate change. We developed a cascade modeling chain to project future bivariate hydrological drought characteristics in 179 catchments over China, using 5 bias-corrected GCM outputs under three shared socioeconomic pathways, five hydrological models and a deep learning model. Our hybrid model also projected substantial GDP and population exposures by increasing bivariate drought risks, suggesting an urgent need to design climate mitigation strategies toward a sustainable development pathway.

In this revision, all the reviewers' concerns have been addressed. Changes made in the revised manuscript are coloured in blue. We sincerely hope you will find the revised version of the paper appropriate for publication. All authors have reviewed the paper and agree to the resubmission of the manuscript. We look forward to hearing from you.

Sincerely yours,

Associate Professor, Wuhan University, China

Honorary Research Associate, University of Oxford, UK

Reply to Reviewers' comments

Legend

Reviewers' comments

Authors' responses

Direct quotes from the revised manuscript

Associate Editor:

Thank you for including a road map of your paper at the end of the introduction. Authors might also mention the section numbers where every topic is presented. I will not delay discussion any further and will start review and discussion.

Reply: We have rephrased this section in the revised Introduction as follows:

This study illustrated the used materials and methods in Section 2 and Section 3, respectively. We compared SRI and TWS-DSI in assessing drought conditions in Section 4.1. The contribution of meteorological factors to simulate streamflow and the calibration of hybrid terrestrial models were shown in Section 4.2. The evolution of univariate droughts was projected in Section 4.3. The bivariate droughts of future scenarios and associated socioeconomic exposures were evaluated in Section 4.4. We discussed the uncertainty of our analysis and main limitations of this study in Section 5, and finally summarized our work in Section 6.

Reviewer #1:

1. In Line 59, I'm not sure about the relationship between these two sentences. Can the author's example support the previous sentence? In my opinion, it seems like it cannot.

Reply: We have rephrased these sentences in the revised Introduction as follows:

China's socioeconomic development, and particularly its agricultural sector, is threatened by the rapid intensification of extreme hazards under climate change (Piao et al., 2010). Over the past years, China has been hit by severe drought events which have caused considerable damage to ecosystem productivity and socio-economic growth (Zhai and Zou, 2005; Yin et al., 2023). For instance, one extreme drought in Sichuan Province in 2022 resulted in power shortages and led to economic losses of 669 million dollars. Water shortage is also a key challenge that hinders the sustainable development of the North China Plain (Chen and Yang, 2013). Over the period of 1985-2014, drought accounted for about 19% of economic losses among all meteorological hazards (Chen and Sun, 2019). With continuing global warming, the economic losses from severe drought events might

increase by over ten billion US dollars per year by the late 21st century, underscoring the importance of projecting future droughts over China (Lu et al., 2023).

2. In the last paragraph of the Introduction section, it is recommended that the author use the past tense when describing the work done in this paper.

Reply: These sentences have been corrected to past tense.

2. The title of section 5.3 of the article is "Suggestions for drought mitigation in China", but I didn't seem to find any relevant suggestions based on the research results in this section (maybe I misunderstood?). In my opinion, the author presented the research background and significance of the paper to readers in section 5.2, but did not provide reasonable suggestions for reducing drought events in China. I think this is also of interest to readers, and I suggest that the author engage in a detailed discussion of this part of the content.

Reply: Thank you; we have provided more details about the relevant suggestions in the revised Section 5.3 as follows:

The Intergovernmental Panel on Climate Change (IPCC) has emphasized that projections of future climate trends can equip policymakers with the scientific insight needed to navigate the challenges of climate change (Pörtner et al., 2022). The results of this study aim to alert policymakers to drought risk in Southwestern China which was just hit by severe drought events and expected to significantly intensify with climate change. We strongly highlight the importance of strictly implementing carbon emission reduction initiatives and developing prevention programs to limit potential drought losses. Preserving local ecological balance and employing rational use of water resources could be the key to mitigating potential losses from extreme droughts (Sohn et al., 2016; Chang et al., 2019). Although China has constructed hydraulic structures with a total water storage capacity of over 7,064 billion m3, current irrigation facilities need to expand to mitigate the challenge of drought under climate change (Xiao-jun et al., 2012; Cai et al., 2015). In addition, it is also beneficial for policymakers that establish a drought information system to get a comprehensive collection of drought impacts from all potential sectors, which can link the government and research organizations (Wilhite et al., 2007).

3. The author is suggested to abbreviate the content in Section 5.2 and include it in the summary section after the conclusion.

Reply: We have revised accordingly and summarize in the revised Section 5.2 and Section 6 as follows:

The uncertainty caused by underlying surface situation and the coupling relationships behind interrelated variables remain unexplained in this study. Therefore, revealing interactions among multisource data is important to understand how the drivers affecting the water cycle under climate change. Here, only five GCM outputs and one in situ observation dataset were used to drive our HTM models. The sparse dataset may undermine the robustness of the approach. Providing a larger number of GCMs and observational data to assemble a more sophisticated model might be an effective approach to improve the accuracy and reliability. On the other hand, due to the heterogeneity of different climatic regions in China, we would like to expand hydrological models (e.g., the weather research and forecasting model hydrological modeling system, soil and water assessment tool or the hydrological modules of land surface process models) to reduce uncertainty in future research. Finally, the GDP and population projections cannot well reflect future economic development and population migration, especially the governmental interference in immigration and economic policies. It is better to consider the dynamic impact of human management on socioeconomic development, which is essential for the construction of a more reliable projection framework.

Our study is insufficient in the revelation of drought hazard drivers and needs to expand datasets and hydrological models to promote the reliability of simulation in future studies. We would also like to take governmental interference of economic and demographic policies into consideration.

4. The last sentence of the paper's conclusion, in my opinion, suggests that drought events are just one of the possible disasters that may be exacerbated by climate change, and the author did not discuss the connection between achieving carbon neutrality goals and drought events. Perhaps I did not express myself clearly, but what I meant was that there was no corresponding data in the paper to support the latter half of the sentence.

Reply: We have rephrased this sentence in the revised Section 6 as follows:

Our findings demonstrate that China will face higher drought risks in a warmer future, emphasizing the urgency of implementing strategies to reduce carbon emissions.

5. I noticed that the author used five hydrological models to conduct experiments, but these models all have some limitations to varying degrees. For example, how did the author consider the applicability of the XAJ hydrological model in different climatic regions, and whether the model parameters obtained using the SCE-UA algorithm are universal? Are these parameters effective if spatial heterogeneity is strictly considered? In addition, the author's introduction of these five hydrological models is too brief, and it is suggested that the author provide slightly more detail in this section. Furthermore, can the author try to use hydrological models such as WRF-Hydro, SWAT, or the hydrological modules of land surface process models to conduct experiments in this paper? In my opinion, these general hydrological models would be more convincing.

Reply: As the hydrological models might show uncertainties, we employed five different models as candidates to simulate streamflow. In implementing this process, we calibrate our models in each catchment. In other words, the parameters of hydrological models in different catchments are not universal. We have provided more details about the hydrological models in revised Section 2.3.1 as follows:

The XAJ (Xinanjiang) model is a hydrological model, which can usually achieve better performance in humid and semi-humid areas than in arid areas (Zhao, 1992). As the model was developed based on the underlying surface of the Yangtze River Basin in China, it is composed of a three-layer evapotranspiration module with four parameters and separates the runoff into four components (i.e., surface water, groundwater, interflow water and flow routing) (Tian et al., 2013). To date, it is widely reported that the XAJ model usually shows the best accuracy in simulating hydrological conditions in China (Hu et al., 2005). However, due to inadequacies in the simulation of arid regions, the results of the XAJ model did not be considered as the best option in northern China.

We use the SCE-UA (Shuffled Complex Evolution) approach to maximize the objective function (i.e., Kling-Gupta efficiency) to optimize these models (Duan et al., 1992). The most complete 20-year observation period is selected to calibrate five models in each watershed. To calibrate the hydrological models, a cross-validation method developed by Arsenault et al. (2017) is used for calibration, which employs the odd years of data to calibrate models, and the even years of data to validate. As catchments are located in different climatic regions, the parameters of models are calibrated for each catchment, which means that the parameters are not universal. Although uncertainties shown by hydrological models are ineradicable, the overall uncertainty is acceptable in the current scale after optimizing five hydrological models for each catchment.

We believe your suggestion of using WRF-Hydro and SWAT models is great, but it beyond the scope of this manuscript. We have discussed the future application in the revised Section 5.2 as follows:

On the other hand, due to the heterogeneity of different climatic regions in China, we would like to expand hydrological models (e.g., the weather research and forecasting model hydrological modeling system, soil and water assessment tool or the hydrological modules of land surface process models) to reduce uncertainty in future research.

Reviewer #2:

1. Text errors should be addressed:

- In line 384, please remove the redundant period.
- In line 198, is it supposed to be 'retained' instead of 'retailed'?
- In line 278, 'demote' should be revised to 'denote'.

Reply: These errors have been corrected.

2. The titles in Figure 10 are suggested to be revised, as they only include severity and duration under SSP1-26 and SSP3-70, which isn't consistent with the elaboration in section 4.3.

Reply: The elaboration in the manuscript is correct, and the title error of this figure have been corrected.

3. In lines 222 and 223, the number of HTMs differs from subsequent elaboration in line 284. The number of HTMs should be corrected.

Reply: We have corrected the number of HTMs in lines 284 to ten.

4. In lines 235 and 401, tables of drought classification and candidate distributions are suggested to be referenced from the supplement file.

Reply: We have provided citations in the revised Section 2.4 as follows:

The hydrological drought classification and ranges indicated by SRI are shown in Table S1.

Based on the maximum Bayesian Information Criterion (BIC), we select the best-performing marginal distributions for duration and severity from seven candidate distributions shown in Table S2, based on historical data for each catchment.

5. In Figure 6, considering the limited number of stations located in Northwestern China and the use of interpolated methods for calculating sensitivities, does it potentially affect the accuracy of the analysis? The author is suggested to elaborate on the reliability of the results in section 4.2.

Reply: We have provided an explanation in the revised Section 4.2 as follows:

Due to the sparse number of observation stations in Northwestern China, the reliability of the sensitivity analysis for these regions is lower than that of the dense observed areas.

6. In line 375, the author is suggested to revise this conclusion. First, it should be mentioned which type of drought is sensitive to temperature. Second, whether the feedback of drought to temperature is reliable should be discussed, as drought is affected by both hydrological and thermal factors. Univariate sensitivity isn't a powerful support under global warming.

Reply: We have rephrased this conclusion in the revised Section 4.2 as follows:

The temperature has a positive contribution to streamflow generation in Northeast China, suggesting a potential mitigation for the deficiency of surface flow. However, there is interactive feedback between hydrological and thermal factors that result in an inability to directly assess the impact of temperature on hydrologic droughts.

7. The author is suggested to add an explanation of which approach was used for the analysis in section 4.2. Is this analysis conducted at spatial, temporal, or spatial-temporal dimensions? More specifically, is the input data for the RF model the multi-year average of each variable from each grid (spatial), or spatial average at each timestep (temporal), or variable for each timestep for each grid (spatial-temporal)?

Reply: We have provided an explanation in the revised Section 4.2 as follows:

We quantified the sensitivity of seven historical mean meteorological variables (i.e., pr, ps, SH, RH, srlds, srsds, temperature) to monthly streamflow in each grid.