Title: Spatiotemporal variation of growth-stage specific compound climate extremes for rice in South China: Evidence from concurrent and consecutive compound events

Response to Reviewer Comments (RC1):
'Comment on esd-2024-8', Anonymous Referee #1, 30 May 2024

This paper investigates the combined climate extremes relevant to rice production in China. The authors analyze concurrent and consecutive compound events relevant for single- and late-rice during 1980–2014, using specific known thresholds. Examining both concurrent and consecutive extremes provides a more comprehensive picture of potential stress on rice crops. However, the manuscript would benefit from addressing some fundamental points and key concerns:

RE: Thank you so much for your comments and suggestions on our manuscript. We have responded to the comments and suggestions point-by-point below (in blue).

Major concerns:

RC1.1 Sample Size Concerns: First concern is regarding the sample size of stations, highlighting the potential lack of representativeness for the entire region. Given the substantial spatial heterogeneity of soil moisture, the limited number of stations may not fully capture the diverse conditions across China.

RE: Thank you for the question. Indeed, the current version of our study have limited sample due to limited number of agrometeorological stations. In order to enlarge the sample size, per the suggestion from reviewer #3, we have decided to use gridded climate data of the rice cultivation areas in southern China (in this study we only focused on southern China without considering rice cultivation regions in Northeast China). We use the gridded observation climate data from CN05.1 (0.25°×0.25°) (Wu J. & Gao, 2013). This dataset has been regarded as the best choice of gridded climate forcing data in mainland China area and has been most widely used in previous studies (Li et al., 2022; Yang et al., 2017; Zhu & Yang, 2020). We use the distribution maps of single-rice (Shen et al., 2023) and late-rice (Pan et al., 2021) for year 2020 as the southern China rice growing area mask. The spatial resolution of this rice distribution data was 10 m. As one single climate grid convers many 10-m rice pixels, we selected climate grids with rice pixels ≥5% area of each 0.25°×0.25° grid. With the update, our sample sizes increased from 28 stations to 2262 grids for single-rice and from 37 stations to 1383 grids for late-rice (Fig. R1). The updated sample size would be sufficient for subsequent statistical analyses.

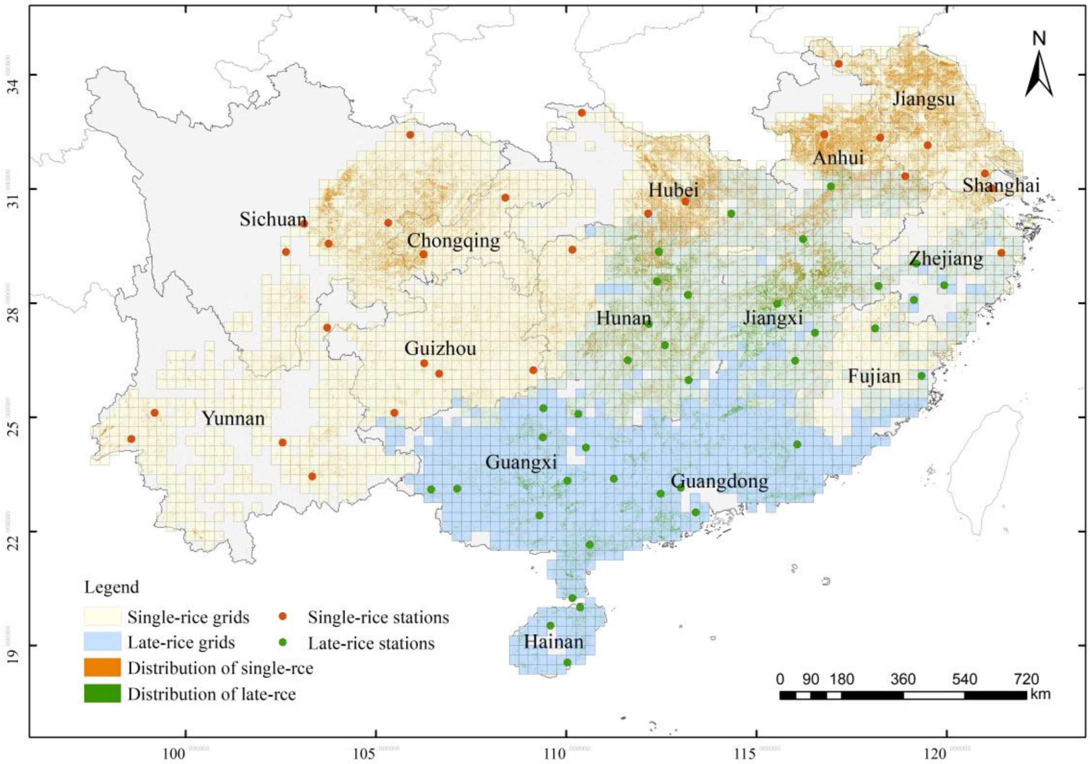

Figure R1. Comparison map of station samples and updated raster samples in the study area.

RC1.2 Missing Yield Impact Assessment: While the paper mentions rice yield as motivation, it lacks a direct evaluation of how these compound events affect production quantities. It is necessary to incorporate an analysis of yield data to directly assess the impact of compound events on rice production. The paper's association with rice is primarily through growing season definitions, yet there is a noticeable absence of yield estimation. The justification for focusing on rice should be more explicit, particularly considering the absence of yield data.

RE: Thank you for your suggestions. We have tried to assessed the actual impact of climate indicators on yield (Fig. R2). Tentatively, we have firstly finished the evaluation of late rice against compound chilling-rainy events.

Here, we used AsiaRiceYield4km data (H. Wu et al., 2023) as the yield raster data, covering the period of 1995 to 2015. It is so far the dataset that provides the longest time-series covering whole China rice cultivation areas. Rice yield data with even longer time-series could only rely on the agrometeorological stations, which would again suffer from the sample size issue. To measure the impact, we followed Ye (Ye et al., 2015) by using detrended yield anomaly to remove the spatial difference in yield.

For the intensity of events, we used severity indicators based on suggestion-RC1.4. For chilling, we used the cold-degree-days of the growth stage as the severity. The cumulative deficit of average daily temperature (Tmean) ≤20°C for three or more consecutive days:

$$CDD_{stage} = \sum_{i=1}^{n} |TEM_{base} - TEM_i|$$

CDD_{stage} represents the cold-degree-days for each growth stage. i is the index of the day within the consecutive days that meet the condition. TEM_i is the mean daily temperature value on day i. TEM_{base} is the mean daily temperature threshold (20°C during Heading-flowering stage (stage#2) and 17°C during Grain filling stage (stage#3), according to our threshold indicated in the manuscript. n is the number of consecutive days that satisfy the condition (at least 3 days).

For the impact of rainy event, we used the cumulative precipitation greater than or equal to 25 mm for three or more consecutive days. A daily 25mm rainfall was classified as the rainy in <QX/T, 468-2018, Code of Agricultural Meteorological Observations-Rice > for precipitation:

$$PDD_{stage} = \sum_{i=1}^{n} |PRE_i - PRE_{base}|$$

PDD_{stage} represents the precipitation-degree-days for each growth stage. i is the index of the day within the consecutive days that meet the condition. PRE_i is the daily precipitation value on day i. PRE_{base} is the daily precipitation threshold (25 mm). n is the number of consecutive days that satisfy the condition (at least 3 days).

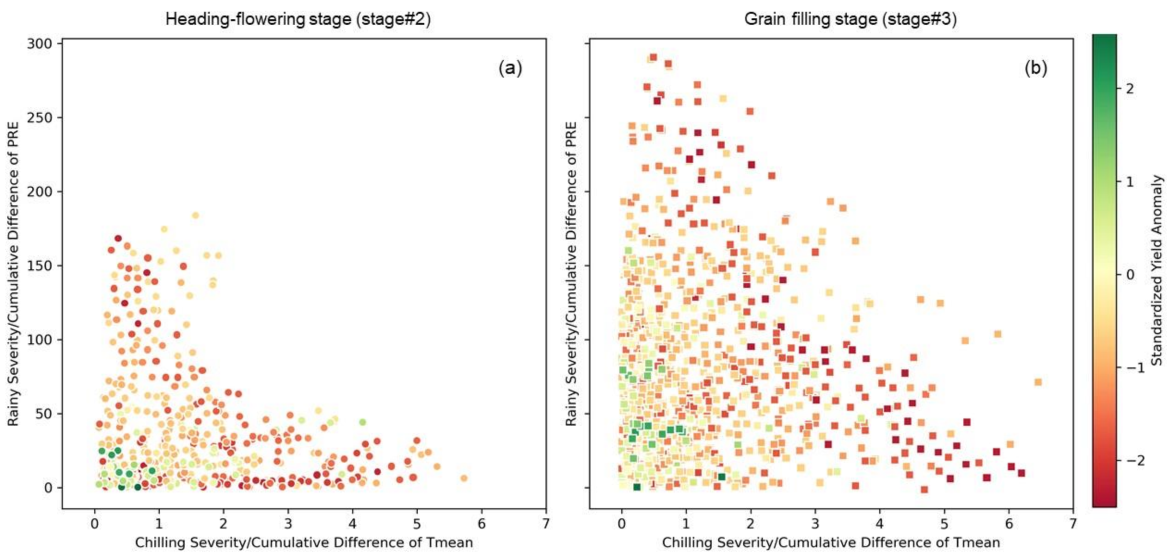

Figure R2. Late-rice yield responses to severity of chilling (temperature) and rainy (precipitation) variation. Color bands indicate the value of the yield anomaly.

Several interesting things could be observed from the figures:

1) There is a clear compound impact of chilling-rainy events on late rice. As severity of chilling

or rainy events increased (from the bottom left to the top right of the graphs), yield decreased. The scatters indicate a weakly convex set of isolines, indicating a weakly stronger yield impact than the linear average of single events, that said, the compound impact of having chilling-rainy together would be stronger than the linear combination of the impacts from each stressor.

2) The impact was more severe the Heading-flowering stage (stage#2) than in the Grain filling stage (stage#3), although there were much less compound events in stage #2 than in stage #3 stage. Negative yield anomaly occurred at smaller values of severity in Fig. R2(a) than that in Fig. R2(b).

Due to the limited time of writing up this response, we have not yet finished the rest part of the analyses, i.e. the impact of concurrent heat-drought events on single rice, and the consecutive events.

RC1.3 Growing Season Definition Clarity: Specifying whether the growing season definition has fixed planting and harvest dates or adapts based on actual planting times is crucial. Sensitivity analysis to choice of dates is necessary to understand how changes in the selection of growing season start and end could influence the results.

RE: In the present version, we used actual planting times (differing year-by-year) as we have sufficient agrometeorological station records to do so. As we are proposing to capture the climate extremes for different phenological stages, timing really matters. For instance, the flowering stage has only 7-10 days, and the interannual variation of phenological dates could sufficiently affect the detection of climate extremes in this stage should a fixed dates be used.

RC1.4 Intensity Metric Considerations: The current focus on number of extreme days based on thresholds might overlook the intensity of extreme events. Analyzing the magnitude of temperature or drought deviations could provide deeper insights. The metrics employed in the study center on frequency and the number of days above a threshold but fail to consider the intensity of compound events. It is important to consider the intensity, as a single day with a temperature 10°C above the threshold could have more substantial implications for agriculture than ten days with only 0.5°C above the threshold.

RE: We strongly agree with reviewer #1's suggestion to include an intensity indicator. The existing literature has proposed three indicators to descript an extreme event: intensity, duration, and severity (Haqiqi et al., 2021)(Fig. R3). According to this reference, we have decided to use severity in the revision, which combines both the duration and intensity of the extreme event based on the cumulative deviation from the threshold for each type of extreme event. For instance, in our impact analysis shown earlier, we have tried to use cold degree days for chilling stress, and cumulative rainfall above 25mm (daily) for rainy stress. Tentatively, they seemed capable to capture the compound impact on yield. Later, we will test on compound heat and drought. When we derive the severity of the compound event, we plan to derive the bivariate probability as the measure of intensity of the compound event, by using copulas and survival Kendall return periods approach or similar approaches.

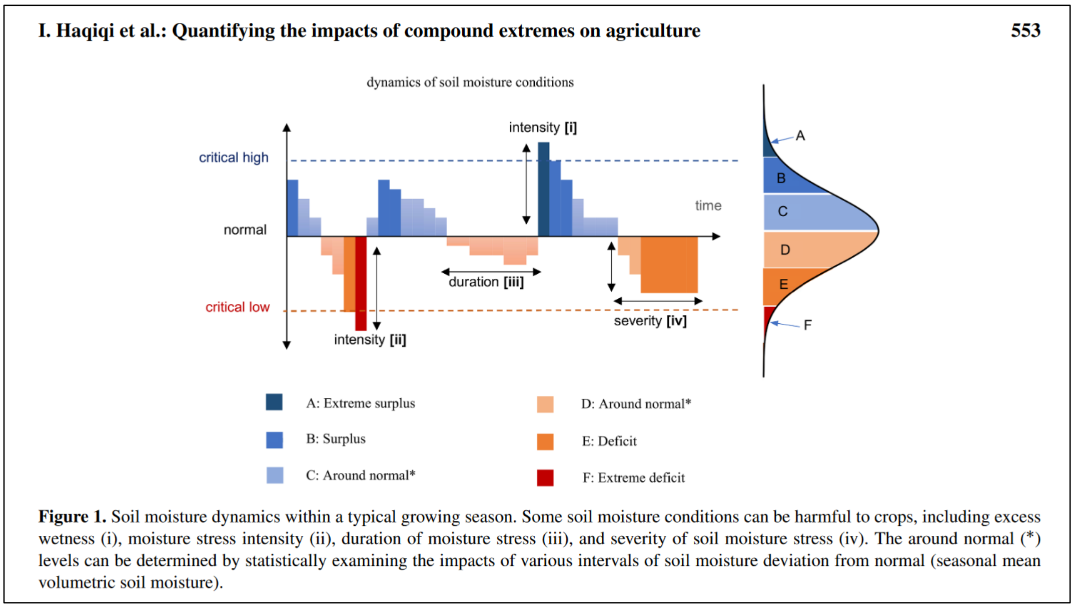

Figure R3. Reference chart for the definition of severity (https://doi.org/10.5194/hess-25-551-2021).

RC1.5 Practical Implications and Value Added: Explicitly discussing the practical applications of the research and its contribution to existing knowledge would enhance the paper's value for the scientific community.

RE: Our study has three particular values.1) While most previous studies have used relative thresholds to define climate extremes, our study considers the physiological responses and thresholds of specific crops. Therefore, the results provide the most accurate view of the extreme events. 2) Crop sensitivity to climate extremes varies by growth stage and event type. Unlike previous studies conducted over the full growing season, our study carefully distinguishes between the three growth stages of rice (the jointing-booting stage (#1), the heading-flowering stage (#2), and the grain-filling stage (#3)). This study at the scale of the remaining rice stages allows us to see the differences in crop impacts of extreme events occurring at different growth stages. 3) At the sub-growth stage scale, we distinguish between multiple types of compound events (concurrent and consecutive climate extremes) that can occur. Combined with the newly added yield impact assessment section (RE1.2), our results are able to see the impact of different types of compound events on rice yields.

References:

Haqiqi, I., Grogan, D. S., Hertel, T. W., & Schlenker, W. (2021). Quantifying the impacts of compound extremes on agriculture. *Hydrology and Earth System Sciences*, *25*(2), Article 2. https://doi.org/10.5194/hess-25-551-2021

Li, Z., Liu, W., Ye, T., Chen, S., & Shan, H. (2022). Observed and CMIP6 simulated occurrence and intensity of compound agroclimatic extremes over maize harvested areas in China. *Weather and Climate Extremes*, *38*, 100503. https://doi.org/10.1016/j.wace.2022.100503

Pan, B., Zheng, Y., Shen, R., Ye, T., Zhao, W., Dong, J., Ma, H., & Yuan, W. (2021). High Resolution Distribution Dataset of Double-Season Paddy Rice in China. *Remote Sensing*, *13*(22), Article 22. https://doi.org/10.3390/rs13224609

Shen, R., Pan, B., Peng, Q., Dong, J., Chen, X., Zhang, X., Ye, T., Huang, J., & Yuan, W. (2023). High-resolution distribution maps of single-season rice in China from 2017 to 2022. *Earth System Science Data*, *15*(7), 3203–3222. https://doi.org/10.5194/essd-15-3203-2023

Wu, H., Zhang, J., Zhang, Z., Han, J., Cao, J., Zhang, L., Luo, Y., Mei, Q., Xu, J., & Tao, F. (2023). AsiaRiceYield4km: Seasonal rice yield in Asia from 1995 to 2015. *Earth System Science Data*, *15*(2), 791–808. https://doi.org/10.5194/essd-15-791-2023

Yang, F., Lu, H., Yang, K., He, J., Wang, W., Wright, J. S., Li, C., Han, M., & Li, Y. (2017). Evaluation of multiple forcing data sets for precipitation and shortwave radiation over major land areas of China. *Hydrology and Earth System Sciences*, *21*(11), 5805–5821. https://doi.org/10.5194/hess-21-5805-2017

Ye, T., Nie, J., Wang, J., Shi, P., & Wang, Z. (2015). Performance of detrending models of crop yield risk assessment: Evaluation on real and hypothetical yield data. *Stochastic Environmental Research and Risk Assessment*, *29*(1), 109–117. https://doi.org/10.1007/s00477-014-0871-x

Zhu, Y.-Y., & Yang, S. (2020). Evaluation of CMIP6 for historical temperature and precipitation over the Tibetan Plateau and its comparison with CMIP5. *Advances in Climate Change Research*, *11*(3), 239–251. https://doi.org/10.1016/j.accre.2020.08.001