Title: Spatiotemporal variation of growth-stage specific concurrent climate extremes and their yield impacts for rice in southern China

Response to Reviewer Comments (RC1):

'Comment on egusphere-2025-1393', Anonymous Referee #1, 20 May 2025

The manuscript presents a well-designed and timely study on the correlation between compound climate extremes and rice yields in southern China, with clear relevance to climate change adaptation. The authors leverage growth-stage-specific physiological thresholds, multi-source gridded data, and compound severity metrics to offer new insights into how concurrent heat-drought and chilling-rainy events affect rice production. This work makes an important contribution in the construction of metrics for compound stressors. However, several points require clarification, and improvements in structure and presentation would significantly improve the manuscript.

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 Comments:

RC1.1 Ambiguity in Drought Stress Severity Definition. The calculation of drought severity appears to exclude events shorter than 10 days, regardless of intensity. Please clarify whether severity is accumulated continuously or only calculated if a 10-day event threshold is met. For rice, a very low soil moisture period, even for a week, can be fatal. Justification for this duration cutoff should be provided, ideally based on physiological or agronomic evidence.

RE: Thank you for the question. The calculation of drought severity accumulates from Day 1 (the onset of soil moisture falling below the defined threshold). However, we retain and analyze only events persisting for ⩾10 consecutive days. The threshold of ten days was applied based on physiological and agronomic relevance and experimental evidence.

Drought development in field environments (especially paddies) is gradual (Perdomo et al., 2015), hence in the existing literature, experiments usually adopts relatively long duration for drought stress. For instance, in a study evaluating drought stress effects on growth, yield, and physiological activities of rice varieties, the drought treatment duration was set to 14 days (Amin et al., 2022). A field investigation assessing seven rice cultivars under continuous irrigation regimes established drought exposures averaging 60 days to examine yield potential under water stress (Barnaby et al., 2019). Research on high temperature and water stress impacts during heading and grain filling stages implemented targeted 10-day drought treatments at heading phase to analyze pollen development and grain quality (Duan et al., 2012). An evaluation of long-term combined heat and water deficit stress on global crops imposed minimum 40-day drought treatments to quantify impacts on plant growth and water-use efficiency (Perdomo et al., 2015). What’s more, the long-term stress (>20d) alters growth and water-use efficiency, no evidence confirms significant yield reduction from short-term stress (Costa et al., 2021).

The impact of short-duration drought on rice remains debated. While extremely severe but brief droughts can be fatal, in some cases, rewatering after short-term stress can promote growth and increase biomass. During vegetative stages, drought enhances soil aeration and root-shoot ratio, improving nutrient/water uptake without compromising growth; while in reproductive stages, short-term drought triggers compensatory recovery post-stress, potentially accelerating grain filling without yield loss (Chi et al., 2001; Jiang et al., 2019; Li et al., 2005). To minimize the influence of these uncertain effects, we set a 10-day threshold to exclude short-duration drought events.

According to China's national standard for agricultural drought classification (Grade of agricultural drought-GB/T 32136-2015), relative soil moisture below 25% is classified as "extremely severe" drought. We analyzed the histogram of relative soil moisture in our study area and during the phenological stages of interest. The results showed that extremely severe drought events are relatively rare in frequency, with the cumulative frequency of single-day relative soil moisture ⩽ 25% accounting for only 4% of the total histogram frequency (Figure R1). Therefore, we believe that excluding short-period droughts does not overlook a major portion of impactful drought events.

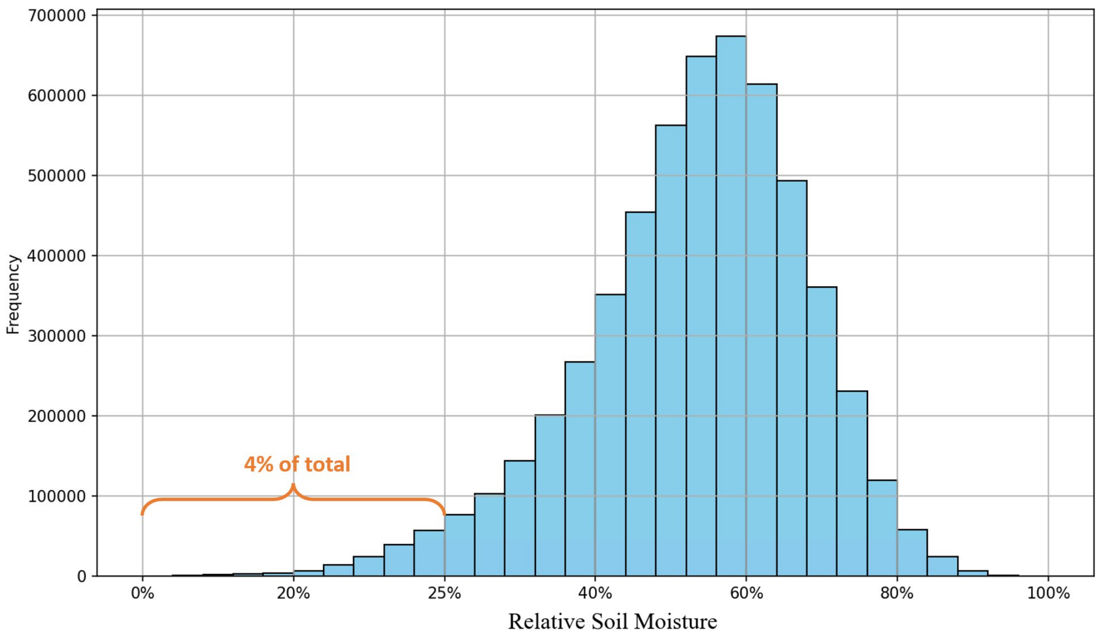

Figure R1. Histogram of single-day relative soil moisture during rice phenological stages across all stations. Bars with relative soil moisture ⩽ 25% account for 4% of the total frequency.

Considering rice's recovery capacity, the hydrological buffering of paddy systems, and the low frequency of extremely severe drought, the 10-day threshold serves to filter out transient fluctuations while retaining events that pose a high risk of physiological disruption. We have incorporated this rationale, along with the explanation of the threshold-based continuous accumulation method, into the revised Methods section of the manuscript.

RC1.2 Clarification of Kernel Density Estimate. Figures 2a and 2c are labeled as Kernel Density Estimates (KDEs), but the x-axis represents time (e.g., 1981–2018), which is not standard in KDE applications. It is confusing what variable is being smoothed, and how the density values should be interpreted. If these are smoothed frequencies or rolling densities over time, the figure should be relabeled or revised accordingly. I recommend providing a more detailed explanation of the construction, including the variable used, kernel type, bandwidth selection, and the interpretation of density on a time axis.

RE: Sorry for the confusion caused by the Figures 2a and 2c. After careful reconsideration, we have decided to remove all KDE visualizations (Figs 2a/c). Instead, we have created separate bar plots for heat-drought (H1D1/H2D2/H3D3) and chilling-rainy (C2R2/C3R3) events (Figure R2). We have updated all relevant figures in the manuscript (Section 3.1) and supplemented the Methods section (2.5) with full implementation details.

We recognized a fundamental methodological mismatch in our initial approach. Applying KDEs directly to event occurrence years resulted in counterintuitive density interpretations along the time axis, as rightly highlighted by the reviewer. In addition, stacking multiple KDEs failed to resolve core visualization challenges. In our original construction:

- Variable Smoothed is the occurrence years of compound events (i.e., each year was a data point).
- Kernel Type: We used a Gaussian kernel.
- Bandwidth Selection: Bandwidth was selected automatically using Silverman's rule of thumb.
- Interpretation on Time Axis: The resulting density curve represented the *estimated probability density function of event occurrence across the years (1981-2018). Peaks indicated years with a higher relative concentration (density) of events, not higher frequency counts.

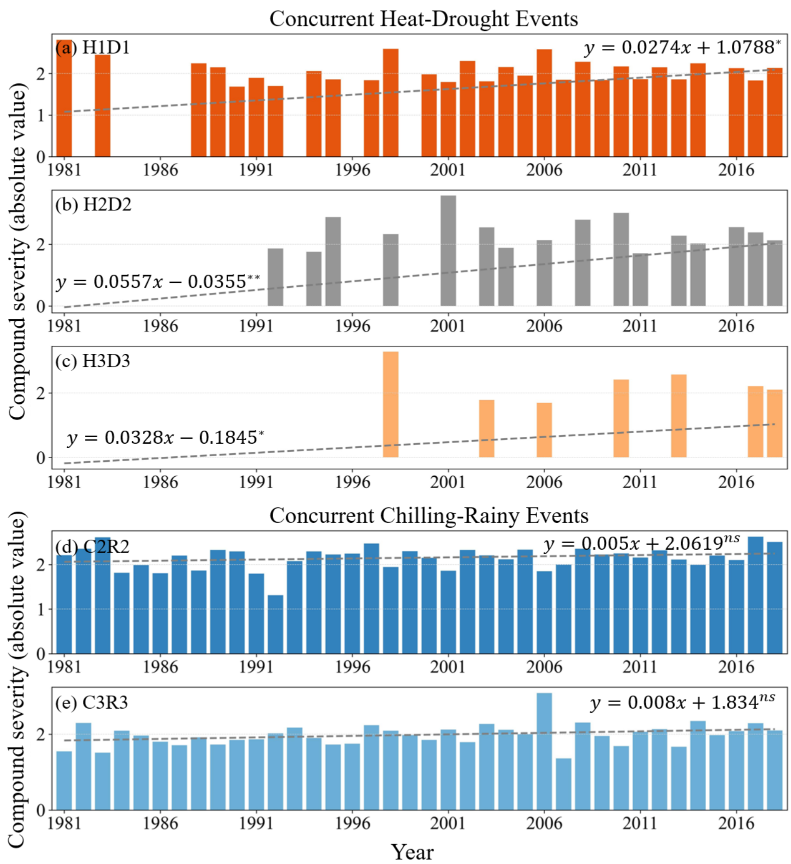

Figure R2. Absolute annual compound severity (CS) of concurrent heat-drought events during jointing-booting stage (a H1D1), heading-flowering (b H2D2), grain filling (c H3D3) for single-rice and concurrent chilling-rainy events during heading-flowering (d C2R2), grain filling (e C3R3) for late-rice for the period of 1981−2018. * indicates significant at the 0.05 Significance level.

RC1.3 Interpretation and Modeling. The analysis relating yield anomalies to compound severity lacks clarity. Both axes in Figure 5 are restricted to negative values, with no explanation for this truncation. Are positive yield deviations and low-stress years excluded? If so, why?

RE: We had some reasons for the negative-axis constraint, but different for X-axis and Y-axis.

X-axis represents Compound severity, and its truncation stems from intrinsic metric properties. In our identification of events, we used the cumulative values surpassing certain threshold to compute severity (of either drought or heat stress), and applied copula fitting to derive joint exceedance probability density, based on which a standardized z-score were obtained to denote the compound severity. By definition, if temperature or moisture did not surpass their corresponding thresholds (as specified in Table 1 in the manuscript), severity will be 0. Correspondingly, we will have a truncation on the X-axis. To some extent, applying the threshold will exclude "low"-stress years, but those thresholds were obtained from national or local Standards, based on intensive field experiments.

Y-axis is about standardized Yield anomaly, derived from the detrended historical yield time series. In our previous version, we excluded positive yield anomalies, by assuming that years with compound climate extremes will strongly have negative yield impacts.

This design stems from the intrinsic properties of our metrics, the negative range of compound stress indices exclusively represents high-stress conditions, while negative anomalies directly measure loss magnitude. Positive values (reflecting favorable conditions, management optimizations, or uncaptured factors) were excluded as they represent distinct regimes, which could obscure the visual salience and scientific focus of the stress-loss relationship.

RC1.4 Final Yield Model. Additionally, the use of simple scatterplots without formal statistical modeling is insufficient, given the complexity of the stress indices. I encourage the authors to fit and report a statistical model or clarify the final equation for this analysis to formally characterize the relationship between yield anomalies and compound stress severity. This would substantiate the visual patterns and improve analysis.

RE: Thank you! In direct response, we have decided to report a statistical model or clarify the final equation for this analysis to formally characterize the relationship between yield anomalies and compound stress severity, in both the method and result sections.

In the method section, we plan to add following information:

To reveal the statistical relationship between yield anomalies (YA_t) and compound severity (CS), simple linear regression analyses were conducted by using the equation below:

$$YA_t = \beta_0 + \beta_1 * CS + \varepsilon$$

where YA_t is the standardized yield anomaly (detrended & normalized). β_0 is the intercept (expected yield anomaly at zero stress). β_1 is the yield loss per unit increase in compound severity). ε is error term.

In the Methods section, we plan to report the fitting statistics and update the Figure 5 caption to report the fitted lines and the fitting statistics. This formal modeling substantiates the visual patterns and provides quantitative measures of stage-specific sensitivity of rice yield to compound climatic stress.

RC1.5: Comments on Manuscript Structure and Flow

Table 2 is referenced in the manuscript but not included.

RE: Sorry! This is a typo. It should be actually Table 1. Will revise.

The manuscript is generally well-organized, but there are several ways the narrative can be improved:

Abstract: Consider simplifying and using more intuitive phrasing to improve accessibility to the general scientific audience.

RE: Thank you for the detailed suggestions. We will follow your instructions to revise the manuscript and narrative, section by section.

RE: We appreciate the suggestion to improve accessibility. We will revise the Abstract to improve clarity and accessibility for a broader scientific readership.

Introduction: The rationale is well-motivated, but some repetition of literature gaps can be consolidated. Move technical details to Methods.

RE: We appreciate this point. To enhance clarity and narrative focus, we will consolidate repeated discussions on literature gaps in the Introduction. Moreover, technical content related to the definitions of compound events and their thresholds has been relocated to the Methods section (Section 2.3). These changes help streamline the Introduction and better emphasize the motivation, context, and scientific gaps addressed in this study.

Methods: While comprehensive, this section is very dense. I suggest creating a labeled subsections on "Compound Severity Metrics" that put together equations and definitions. A flowchart or schematic of the data-processing pipeline would improve readability.

RE: Thank you for the valuable suggestions to enhance readability. We try to implement the following changes:

We will create a dedicated subsection titled "2.4.1 Compound Severity Metrics". This subsection now clearly presents all relevant equations (e.g., the calculation of compound severity), definitions, and the rationale behind the chosen metrics.

We will add a new schematic diagram that visualizes the full data-processing workflow, from meteorological and phenological data input to compound severity assessment and yield impact analysis. This visual will aid improves reader understanding of the methodological framework.

Results: Avoid overuse of code-like labels (C2R2, H3D3) in narrative prose; use descriptive names. Ensure all figures are introduced with clear interpretive framing.

RE: We agree that overusing code-like labels can hinder readability. Throughout the Results section (and the rest of the manuscript), labels such as H2D2, C3R3 will be replaced with descriptive names (e.g., " heat-drought events during heading-flowering stage#2 (H2D2)", "chilling-rainy events during grain filling stage#3 (C3R3)"). Furthermore, we have carefully reviewed the introduction of all figures. Each figure reference is now preceded by clear interpretive framing that explicitly states the scientific question or key finding the figure addresses (e.g., "To identify spatial hotspots of compound stress, Figure 3 shows..." or "Figure 5 reveals the relationship between compound stress severity and yield loss magnitude...").

Figures: Improve color bar labeling and add interpretive guidance in captions. Figures 3 and 5 in particular would benefit from better explanation of axis ranges and unit meanings.

RE: We thank the reviewer for the suggestions to improve figure clarity. We will revise the captions for Figures 3 and 5 as follows, incorporating enhanced color bar labeling and interpretive guidance:

Figure 3 revise caption:

"Spatial distribution of compound severity for concurrent heat-drought events in single-rice (a-c: jointing-booting#1, heading-flowering#2, grain filling stages#3) and concurrent chilling-rainy events in late-rice (d, e: heading-flowering#2, grain filling stages#3) during 1981−2018. Shading represents the magnitude of compound severity (unitless indices where more negative values indicate higher stress severity). Darker shades correspond to regions experiencing more intense compound stress."

Figure 5 revise caption:

"Relationship between compound stress severity and standardized yield anomaly (a-e: for specific growth stages and event types) and bar plot of standardized yield anomaly by growth stage (f) during 1995−2015. Axes are restricted to negative values to specifically focus on the relationship between yield loss magnitude (negative yield anomalies) and high compound stress severity (negative values) during damaging event years. The symbol * indicates F-test significance at the 10% level. Solid lines represent significant linear regression fits ($p < 0.01$) for stress-loss years (see Methods)."

These revised captions provide the necessary context for interpreting the figures, explicitly define the metrics and units, explain the axis ranges (especially for Fig 5), and offer guidance on how to interpret the visualizations.

Discussion: While informative, the discussion can be tightened.

RE: We plan to revise the Discussion section to improve conciseness and focus. Repetitive summaries of Results have been reduced. The section now more efficiently synthesizes key findings, emphasizes their novelty (especially regarding growth-stage-specific thresholds and impacts), places them clearly in the context of existing literature, and robustly discusses implications for adaptation and future research.

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