

Current and projected impacts of extreme climate events on winter wheat yield in Northern China

Corresponding Author: Professor Xiaomao Lin

This file contains all editorial decision letters in order by version, followed by all author rebuttals in order by version.

Version 0:

Decision Letter:

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Dear Professor Lin,

Your manuscript titled "Current and projected impacts of extreme climate events on winter wheat yield in Northern China" has now been seen by 3 reviewers, and we include their comments at the end of this message. They find your work of interest, but some important points are raised. We are interested in the possibility of publishing your study in Communications Earth & Environment, but would like to consider your responses to these concerns and assess a revised manuscript before we make a final decision on publication.

In revision, please address the following editorial thresholds:

* Provide a compelling analysis of impacts of extreme climate events on winter wheat yield in Northern China, including clear comparisons of yield estimations between different methods, full discussions on potential factors influencing yields, and clarifying implications of main findings, all raised by both Reviewer #1 and #2.

* Make a discussion on method limitations, providing robust results.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

Please submit your point-by-point responses as a separate file, distinct from your cover letter where you can add responses to the Editors' comments that you do not want to be made available to the reviewers. Word files are preferred. We recommend that any figures, tables or graphs that are included in the response to reviewers are also included in the main article or Supplementary Information.

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Please do not hesitate to contact us if you have any questions or would like to discuss these revisions further. We look

forward to seeing the revised manuscript and thank you for the opportunity to review your work.

Best regards,

Wenfeng Liu, PhD
Editorial Board Member
Communications Earth & Environment
orcid.org/0000-0002-8699-3677

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- If applicable, a statement regarding data available with restrictions
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

This manuscript investigated the winter wheat yield responses to extreme climate events in Northern China. The work combined a statistical model result and process-based model estimates under historical and future climate for three scenarios. While the manuscript is interesting and provides useful analysis for various phenological stages, there are a few issues/errors that should be addressed.

- There are six sites for model calibration in the CERES-Wheat model within DSSAT, but there are no sites in MYS. How can the results be validated in the MYS region? Are results in this region more uncertain than in the other two regions?
- How do results upscale from site-level to regional scale? How do management (e.g., fertilizer, cultivar, and irrigation) treat in each region given two regions have more than one site?
- There are not model calibration validation results to show the model performance for the historical period for both statistical and process-based model.
- While the manuscript claimed the good agreement between observed and simulated yield responses and used process-based models to identify future climate change effects on yields in Fig 5. However, I saw lots of difference except for Fig 5(a) and Fig 5(i); therefore, use of both methods for future climate change effects should be considered. It's also puzzling why the statistical models are so flat in practically all figures.
- Are Figs. 1 and 2. statistically significant? What is the spatial resolution of these plots? The spatial plots show there are dotted spots; are these consistent in all climate models?
- It is unclear in Fig. S3., which future SSP scenario is? In fact, the projected yield changes in each scenario are not shown. Are projected yield changes in future comparable to other studies?
- Results show consecutive dry days reduce in future climate, but do not consider extreme rainfall effects. Floods can reduce yield in this region as extreme climate events (e.g., Shi et al., 2021) and rainfall could become stronger under climate change, should discuss or/and include floods/extreme rainfall in analysis.

Shi, W., Wang, M., & Liu, Y. (2021). Crop yield and production responses to climate disasters in China. *Science of The Total Environment*, 750, 141147. <https://doi.org/10.1016/j.scitotenv.2020.141147>

Reviewer #2 (Remarks to the Author):

I read this study on assessing extreme climate impacts on winter wheat yields. The authors provide valuable insights into regional wheat vulnerability through their modeling approach. While the manuscript makes significant contributions, I would like to highlight several points that require attention for additional analysis or discussions.

The use of abbreviations in the abstract and the main text is problematic for readers. Consider spelling them out or finding alternative ways to improve clarity in your statements.

Throughout the manuscript, year ranges should use en-dashes rather than hyphens (e.g., "1999–2019" instead of "1999-2019") for proper typographical convention.

The authors study an important agricultural region in North China, but the characteristics of this region are introduced quite late in the manuscript (Figure 7?). An earlier description of the study area would provide necessary context for readers unfamiliar with Chinese agricultural regions.

The rationale behind the simultaneous use of logarithmic transformation and time trend terms in Equation (1) needs further explanation. How does this combination help separate technological trends from climate effects?

The manuscript would benefit from addressing several methodological limitations. The temperature thresholds defining heat stress ($T_{max} \geq 30^{\circ}\text{C}$) and freeze stress require better physiological justification specific to Chinese wheat varieties.

While consecutive dry days serve as a drought indicator, actual soil moisture or antecedent precipitation might better represent plant water stress. It is necessary to incorporate soil moisture for the physiological relevance of drought stress characterization, especially during compound events.

Perhaps here is a problematical issue: the analysis focuses exclusively on rainfed systems when irrigation is prevalent throughout Northern China's wheat production regions (as documented in Li et al., 2024 NPJ Climate and Atmosphere Sciences and Piyush et al., 2024, Nature Water). This critical oversight renders the findings largely irrelevant for real-world agricultural management and adaptation planning. The authors need to clarify this point.

Reviewer #3 (Remarks to the Author):

This is an interesting study focusing on the effects of weather extremes on wheat yield in Northern China. As weather shocks become increasingly important, I believe this research is an important step in understanding food security in the context of increasing weather variability.

My comments are as follows:

(1) In Equation 1, the authors use multiple temperature accumulation indices to quantify chilling, hot, and compound weather

extremes. I noticed that the phenology data they use are from agro-meteorological sites, which are not fixed each year. This raises concerns about potential issues, such as warmer temperatures causing shorter growing durations. For example, if you calculate temperature accumulation for a warmer climate, it might equate to a cooler climate but with a longer growing duration. Could this discrepancy affect the results?

(2) Lines 398–409 mention that the wheat yield data cover the period from 1999 to 2019, while the phenology data span from 1992 to 2013. Why not align these periods to ensure consistency?

(3) It is common for hot days (HD) to have higher EDD and CHD. I suggest that the authors include a co-linearity analysis in the supplementary file to address this.

(4) I recommend moving the section titled “Response of Wheat Yield to Extreme Climate Indices” to the beginning of the paper. This is likely the most interesting thing for readers and should be prioritized.

(6) I also suggest adding a table in the main text to show the response coefficients and standard deviations. This would allow readers to quickly identify the most impactful phases and key climate factors affecting wheat yields.

(7) There is a significant difference between statistical models and process-based models in assessing the impacts of weather extremes. While I agree that some impact processes may not be incorporated into the models, the current discussion on this topic seems disconnected from the conclusions. I did not find a focused discussion on this result in the subsequent sections. Therefore, I recommend either removing the results related to process-based models or adding more discussions to better integrate this results into the paper.

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Version 1:

Decision Letter:

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(1) Addressing the concerns regarding the potential bias in future climate change projections.

(2) Providing a clear and comprehensive clarification of how irrigation is considered (or not considered) in their data sources and modeling approach.

We therefore invite you to revise and resubmit your manuscript, along with a point-by-point response that takes into account the points raised. Please highlight all changes in the manuscript text file.

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Best regards,

Wenfeng Liu, PhD
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Mengjie Wang
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REVIEWER COMMENTS:

Reviewer #1 (Remarks to the Author):

While the authors have addressed some issues, there are still concerns:

*Regarding my comment #4, lines 234-236: These sentences do not appear to be correct in the manuscript. There was no good agreement between observed and simulated yield responses in most panels in figure 6. The authors acknowledge in their response that the apparent differences in yield sensitivity across the panels reflect fundamental distinctions between the statistical and process-based modeling frameworks. Therefore, the projected climate-driven changes in winter wheat yield can be biased using only a process-based model. Therefore, I suggested using both methods for future climate change effects or making some corrections using observations.

*Regarding my comment #2, I agree with the other review that irrigation not being considered in the analysis is a big issue. Could you clarify whether these calibrated stations are irrigated? Do winter wheat yields, planted areas, and production data from the National Bureau of Statistics come from irrigated/rainfed areas or both?

Reviewer #2 (Remarks to the Author):

The authors have addressed some of my technical concerns adequately, particularly the temperature threshold justifications and drought indicator limitations.

However, my main concern about the irrigation issue remains unresolved. Beyond the local cooling effects that the authors mention, irrigation has significant regional and continental-scale impacts on water and energy transport (or downwind impacts, see REFS below). These feedbacks may largely influence the rainfed croplands' climate, such as the extensive irrigation region under this study.

The authors acknowledge that "irrigation is practiced throughout Northern China's wheat production regions" but continue to focus exclusively on rainfed systems. This creates a disconnect because the climate data they use to drive their (statistical) models may already reflect the influence of widespread irrigation on regional climate patterns. In essence, they may be applying "irrigated climate" to simulate "rainfed crops," which could lead to biased estimates of climate sensitivity.

I suggest the authors incorporate the irrigation fraction (in the plot or on the regional scale) as a control variable to validate their current results and findings. Probably, I can see the mitigating effects of irrigation on temperature and drought, particularly in summer.

Some papers about water and heat transport or downwind impacts of irrigations:

Li, H., Keune, J., Smessaert, F., Nieto, R., Gimeno, L. and Miralles, D.G., 2023. Land-atmosphere feedbacks contribute to crop failure in global rainfed breadbaskets. *npj Climate and Atmospheric Science*, 6(1), p.51.

Greve, P., Schmitt, A.U., Miralles, D.G., McDermid, S., Findell, K.L., García-García, A. and Peng, J., 2025. Observational

evidence of increased afternoon rainfall downwind of irrigated areas. Nature Communications, 16(1), p.3415.

Reviewer #3 (Remarks to the Author):

I think the authors have revised the manuscript well. Thanks for letting me review the paper.

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Version 2:

Decision Letter:

<*** REMEMBER TO ATTACH REVISIONS CHECKLIST (WORD)***>

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Dear Professor Lin,

Your manuscript titled "Current and projected impacts of extreme climate events on winter wheat yield in Northern China" has now been seen by our reviewers, whose comments appear below. In light of their advice, we are delighted to publish a suitably revised version in Communications Earth & Environment in principle, provided that you can justify or revise the data inconsistency as raised by reviewer #1.

We therefore invite you to revise your paper one last time to address the remaining concerns of our reviewers. At the same time we ask that you edit your manuscript to comply with our format requirements and to maximise the accessibility and therefore the impact of your work.

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Best regards,

Mengjie Wang

Associate Editor, Communications Earth & Environment
Consulting Editor, Communications Sustainability
Bluesky: @commsearth.nature.com; @commssustain.nature.com

REVIEWERS' COMMENTS:

Reviewer #1 (Remarks to the Author):

*The figure 7 has been included for yield changes from statistical and process-based models, but this result is inconsistent with figure 6. Figure 6 shows more yield reduction for most of extreme climate indices in the process-based model than the statistical model, for example, FDD_DP, CDD_VP, CDD_DP, and CHD_RP. However, Figure 7 shows CDD_VP's yield is lower in the statistical model than in the process-based model, which I do not expect. CHD_RP in Figure 7 is consistent with Figure 6; yield is lower for the process-based model than the statistical model.

Reviewer #2 (Remarks to the Author):

I have no further comments at this time.

However, given the valuable field data available, I was particularly interested in exploring the different responses of rainfed versus irrigated wheat to climate extremes. Maybe this is not the major focus of the study.

Reviewer #3 (Remarks to the Author):

I am good with revision. Thanks

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Point-by-point Responses to Three Reviewers for COMMSENV-25-0409

We greatly appreciate these insightful comments and suggestions to our manuscript. The following pages contain our point-by-point responses to Reviewers' comments. Reviewer's comments are shown in regular fonts, our responses are in blue fonts, and revised manuscripts text is highlighted in red fonts within quotation marks. Also, our revision has been highlighted by yellow in the Main text.

Reviewer #1 (Remarks to the Author) for COMMSENV-25-0409:

This manuscript investigated the winter wheat yield responses to extreme climate events in Northern China. The work combined a statistical model result and process-based model estimates under historical and future climate for three scenarios. While the manuscript is interesting and provides useful analysis for various phenological stages, there are a few issues/errors that should be addressed.

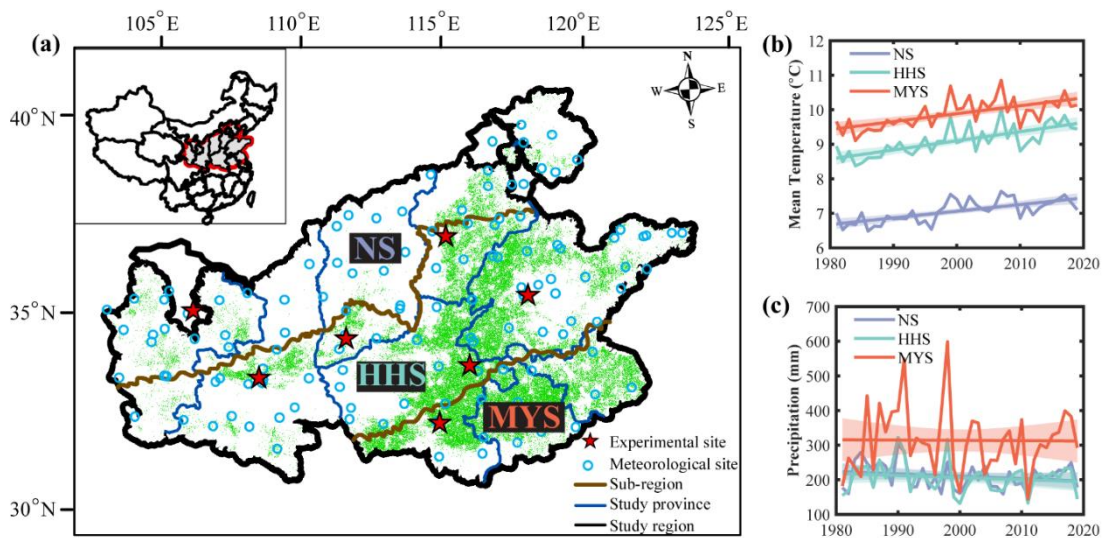
Response: We appreciate your complimentary and encouraging comments. Your comments and suggestions substantially improved the quality of this study. Please check our point-by-point response.

1. There are six sites for model calibration in the CERES-Wheat model within DSSAT, but there are no sites in MYS. How can the results be validated in the MYS region? Are results in this region more uncertain than in the other two regions?

Response: Thank you for your insight. Yes, we agreed with your concern, thus collecting and adding an experimental site, Zhumadian (cultivar “Zhengmai9023”) for our model calibration in the MYS region. Then, we re-simulated the sites in MYS region, updated Fig.1 (originally Fig.7 in Main text) and Table S3 (originally Table S1) in our revision.

Updated Fig. 1 and Table S3 in our revision are as below:

“Fig. 1 Characterization of the study region.



(a) Winter wheat planting patterns (green background map) across each sub-region (North (NS); Middle (Huang-Huai, HHS); South (middle-lower reaches of Yangzi River, MYS)). Blue circles are meteorological observation sites, and red stars indicate locations of experimental sites. (b) Average temperature and (c) Average total precipitation during the winter wheat growing season from 1980 to 2019.”

The data for winter wheat phenology (sowing, anthesis and maturity), cultivar, yield, and management practice for *Zhengmai9023* were collected from agro-meteorological operated by China Meteorological Administration (CMA, <http://data.cma.cn/en>) and Xiao and Tao (2014).

Additionally, we added *Zhengmai9023* cultivar and calibration information in **Table S3** as below:

“**Table S3.** Observed field dataset of representative cultivars for calibration years (normal fonts) and validation years (bold fonts) in the CERES-Wheat model.”

Experimental stations	Cultivar	Soil type	Planting dates (DOY)	Planting year	Yield (kg ha ⁻¹)	Data source
Luancheng (37°53'N, 114°38'E)	<i>Kenong 199</i>	Loam	285	2004	5321	Luancheng Agro-ecosystem Experimental Station
			284	2005	5276	
			284	2006	6249	
Taian (36°10'N, 117°09'E)	<i>Jimai22</i>	Clay loam	288	2008	7441	Qi et al. (2011)
			282	2013	6670	Bian et al. (2016)
			280	2014	6710	
Shangqiu (34°27'N, 115°40'E)	<i>Yumai34</i>	Clay loam	285	2012	6255	Shangqiu Agro-ecosystem
			284	2013	6831	Experimental Station
			284	2014	8264	
Zhumadian (33°00'N 114°02'E)	<i>Zhengmai 9023</i>	Loam	296	2006	5625	Zhumadian Agro-meteorological station and Xiao and Tao (2014)
			299	2007	6225	
			302	2008	6000	
Yangling (34°17'N, 108°04'E)	<i>Xiaoyan2</i>	Loess	263	2007	5135	Zhang et al. (2018)
			268	2009	4500	
			268	2013	4579	
Wenxi (35°20'N, 111°17'E)	<i>Jingmai92</i>	Loess	271	2009	2800	Xue et al. (2019)
			280	2010	2440	Sun et al. (2018)
			276	2013	1880	
Guyuan (35°79'N, 106°45'E)	<i>Xifeng 27</i>	Loess	263	2009	2829	Ren et al. (2016)
			260	2013	5702	Wei et al. (2018)
			264	2014	6135	

Therefore, we accordingly added a citation Xiao and Tao (2014) paper in our SI.

Reference:

Xiao, D., Tao, F., 2014. Contributions of cultivars, management and climate change to winter wheat yield in the North China Plain in the past three decades. European journal of agronomy. 52, 112-122

2. How do results upscale from site-level to regional scale? How do management (e.g., fertilizer, cultivar, and irrigation) treat in each region given two regions have more than one site?

Response: Thanks for your excellent question. To address the upscaling from site-level to regional scale, we followed a multi-step approach. First, we used DSSAT, a point-based biophysical crop model, to simulate wheat yield at the site level using localized climate, soil, and management inputs. The site-based outputs were then spatially interpolated using the inverse distance weighted (IDW) method in ArcGIS for the whole study region. In this method, a neighborhood about the interpolated point is identified and a weighted average is taken of the observed values within this neighborhood. Similar methods can be found in Li et al., 2014; Liu et al., 2014; Wang et al., 2020; and Wu et al., 2006. For our model management setting, the most frequently used and regionally representative cultivars at experimental stations were selected and assumed to be province-specific. Additionally, depending on the availability of data, we also used one cultivar for two provinces to obtain province-specific crop coefficients for the subsequent model analysis, such as the “Kenong199” cultivar at Luancheng station in the Hebei province was also applied in the Beijing and Tianjin simulations. Similar methods can be found in Wang et al., 2018; and Zhao and Yang, 2018.

References:

Li, K., et al., 2014. Low yield gap of winter wheat in the North China Plain. European Journal of Agronomy. 59, 1-12.

Liu, B., et al., 2014. Post-heading heat stress and yield impact in winter wheat of China. Global change biology. 20, 372-381.

Wang, X. Y., et al., 2018. Rice yield potential, gaps and constraints during the past three decades in a climate-changing Northeast China. Agricultural & Forest Meteorology. 259, 173-183.

Wang, B., et al., 2020. Sources of uncertainty for wheat yield projections under future climate are site-specific. Nature Food. 1, 720-728.

Wu, D. R., et al., 2006. Quantifying production potentials of winter wheat in the North China Plain. European Journal of Agronomy. 24, 226-235.

Zhao, J., Yang, X., 2018. Distribution of high-yield and high-yield-stability zones for maize yield potential in the main growing regions in China. Agricultural and Forest Meteorology. 248, 511-517.

3. There are not model calibration validation results to show the model performance for the historical period for both statistical and process-based model.

Response: Thank you for pointing this out. We agreed and added the results for our model calibration and validation. The details of genetic parameters used in our study are presented in **Table S2** in our revision.

“Table S2. Derived genetic parameters of seven cultivars in the DSSAT-CERES-Wheat model.”

Cultivar	P1V	P1D	P5	G1	G2	G3	PHINT
<i>Kenong199</i>	55	75	656	18	38	2	54
<i>Jimai22</i>	57	78	610	17	36	1.5	54
<i>Yumai34</i>	43	63	611	18	42	1.8	55
<i>Zhengmai9023</i>	42	63	600	16	38	1.5	55
<i>Xiaoyan2</i>	49	81	580	19	38	1.8	56
<i>Jingmai92</i>	42	81	580	19	39	2	56
<i>Xifeng 27</i>	42	63	581	21	40	1.8	55

Notes:

P1V: Days required at the optimum vernalizing temperature to complete vernalization (d)

P1D: Relative amount that development rate is slowed when wheat is grown in a photoperiod 10h shorter than the optimum (%/10h)

P5: Grain filling (excluding lag) phase duration ($^{\circ}\text{C}\cdot\text{d}$)

G1: Kernel number per unit canopy weight at anthesis (g^{-1})

G2: Standard kernel size under optimum conditions (mg)

G3: Standard, non-stressed mature tiller dry weight (g)

PHINT: Interval between successive leaf tip appearances ($^{\circ}\text{C}\cdot\text{d}$)

Accordingly, we added our model calibration and validation results in **Fig. S6**. We also added and enhanced the model calibration and validation results in the section of Crop model input and calibration data as below:

Lines 485-488: “Crop parameters and physiological characteristics are given in the form of seven genetic coefficients (**Table S2**). Four phenology coefficients (P1V, P1D, P5, and PHINT) impact plant phenological development, while the other three growth coefficients (G1, G2, and G3) are related to grain yield.”

Lines 500-507: “CERES-Wheat with adjusted genetic parameters exhibited reliable performance for simulating winter wheat phenology from planting to anthesis (ADAT) and planting to maturity (MDAT) (**Fig. S6**). The MAE values were about 4.0 and 4.7 days between simulation and observation for anthesis and maturity days, respectively. Simulated yields showed good agreement with the observations, with an MAE value of 466.7 kg ha^{-1} . The relationship between the observed and simulated yields and phenology dates of winter wheat confirmed that the calibrated CERES-wheat model was robust in reproducing the different yield levels across a wide range of climates in China.”

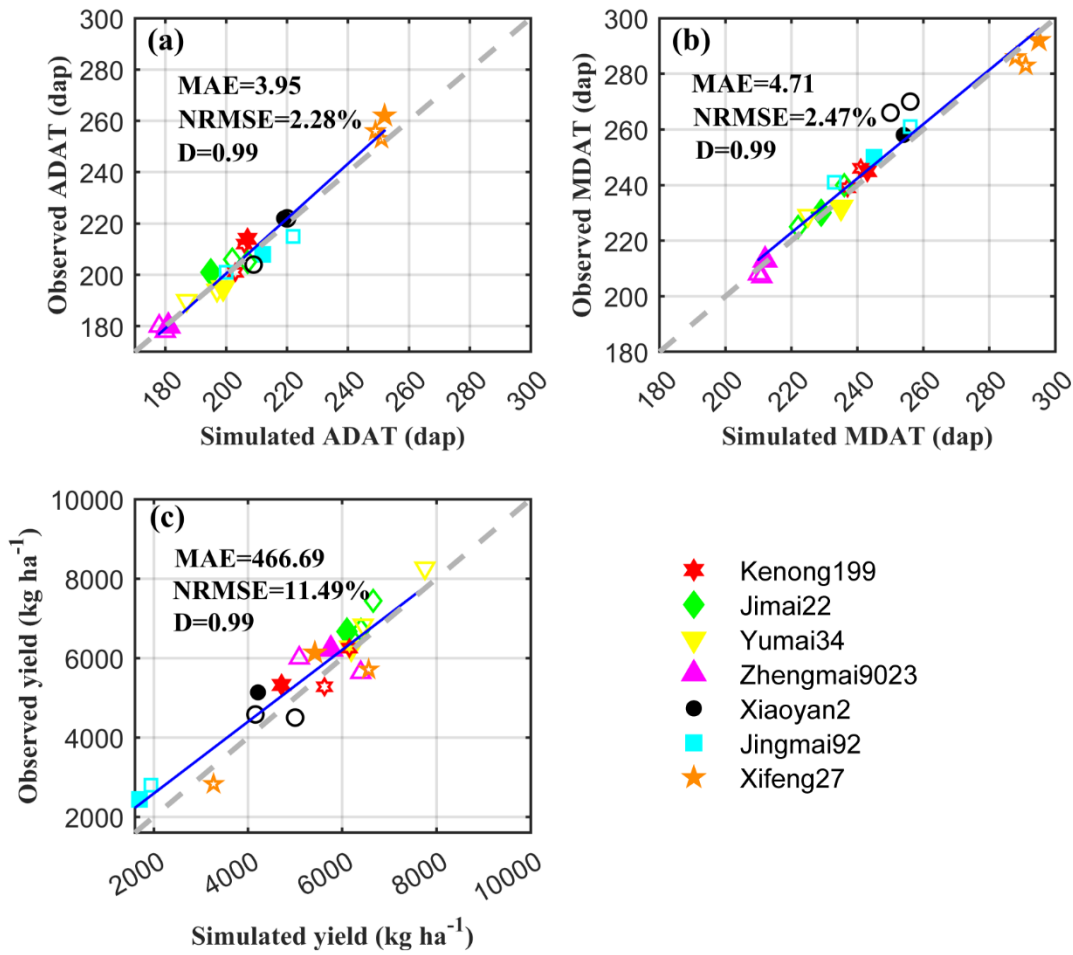


Fig. S6 Comparison of observed and simulated values for (a) anthesis day (ADAT, duration from planting to anthesis), (b) maturity day (MDAT, duration from planting to maturity), and (c) grain yield (kg ha^{-1}). Solid and hollow color-coded symbols indicate calibration and validation data points for seven cultivars used in our study, respectively. The solid blue and dashed gray lines are the regression line and 1:1 line, respectively.

4. While the manuscript claimed good agreement between observed and simulated yield responses and used process-based models to identify future climate change effects on yields in Fig 5. However, I saw lots of difference except for Fig 5(a) and Fig 5(i); therefore, use of both methods for future climate change effects should be considered. It's also puzzling why the statistical models are so flat in practically all figures.

Response: Thank you for your careful review and insightful comments. To evaluate the consistency between modeling approaches, we used two approaches, as one is our statistical model, which estimates functional relationships between climate predictors and observed yields, and then we applied the same climate predictors to fit a new regression model using the process-based simulated yields. The resulting climate sensitivity coefficients from the process-based model were then directly compared to those derived from observed statistics (original **Fig. 5**, now **Fig. 6**).

The apparent differences in yield sensitivity across the panels reflect fundamental distinctions between the statistical and process-based modeling frameworks. In **Fig. 5** (now **Fig. 6**), the statistical model generally produces flatter yield responses to key climate indicators, particularly in panels (a), (b), (e), and (i), suggesting limited responses to interannual variability in extreme events. This pattern stems from the statistical model's reliance on observed yield data, which are confounded by management variability and local adaptation including breeding technologies, making it less sensitive to specific extreme stressors. In contrast, the process-based model (DSSAT) reveals more pronounced and nonlinear yield responses to several climate indices, especially in panels (c) and (f), where yield losses are more clearly captured under increase of heatwave or drought stress. These more dynamic relationships reflect the physiological detail embedded in DSSAT, which simulates crop growth processes mechanistically and responds more explicitly to climate extreme events.

5. Are Figs. 1 and 2. statistically significant? What is the spatial resolution of these plots? The spatial plots show there are dotted spots; are these consistent in all climate models?

Response: These are great questions. Original **Fig. 1-2** shows the spatial distribution of historical and future projected changes (Δ) in extreme climate events. We focus only on spatial distribution in these figures and do not assess their spatial statistical significance. These sub-figures were produced by first calculating extreme climate metrics at the site level, followed by spatial interpolation using the inverse distance weighted (IDW) method in ArcGIS to generate gridded maps across the study region, where the spatial resolution (or output raster cell size (1,000m) in the context of ArcGIS) defined by user-defined cell size is 1 km frequently used for climate and agricultural models. The spatial interpolation method may produce localized circular or dotted patterns around point observations. These are interpolation artifacts that do not affect the actual data values but may influence visual interpretation.

Due to our projected scenarios selected, all sub-figures are visualized based on the ensemble of five climate models (GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0, IPSL-CM6A-LR, and UKESM1-0-LL). To answer whether the trend is consistent in all climate models, we plot both the ensemble average of five climate models and individual model results (these serve as the new SI Figures in our revision). As shown in the updated **Fig. S3 and Fig. S4** (see below), the trends across climate models are generally consistent, indicating that the observed dotted patterns are due to interpolation and not a reflection of model disagreement.

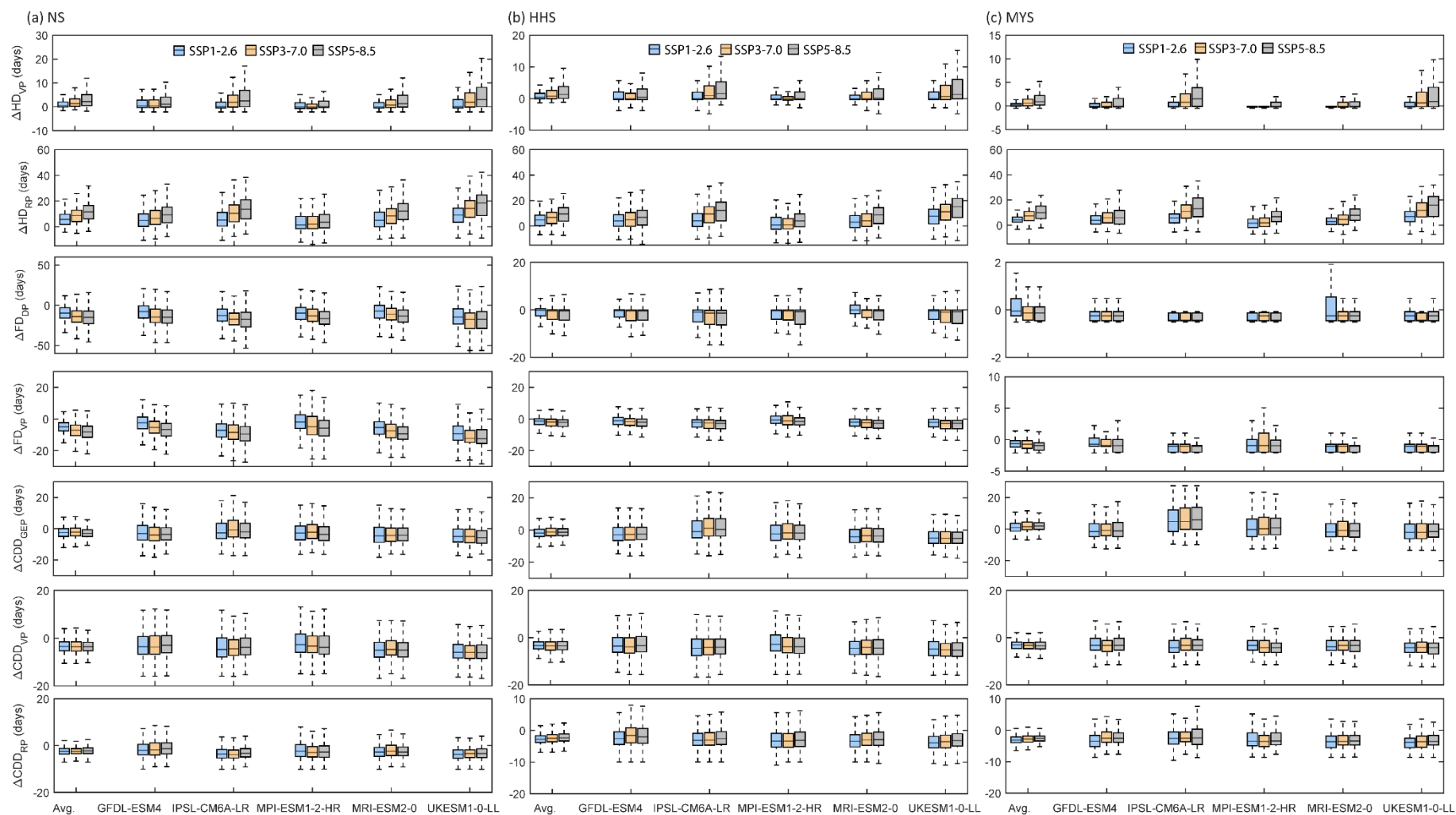


Fig. S3 Boxplot of projected changes for (Δ) hot days (HD), freeze days (FD), and consecutive dry days (CDD) during growth phases under three future climate scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5). Boxplots indicate the median (horizontal line), 25-75th percentile (box), and 5-95th percentile (whiskers) of estimated changes in all year and location combinations for three sub-regions. GEP is the germination and establishment phase (planting to November); DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).

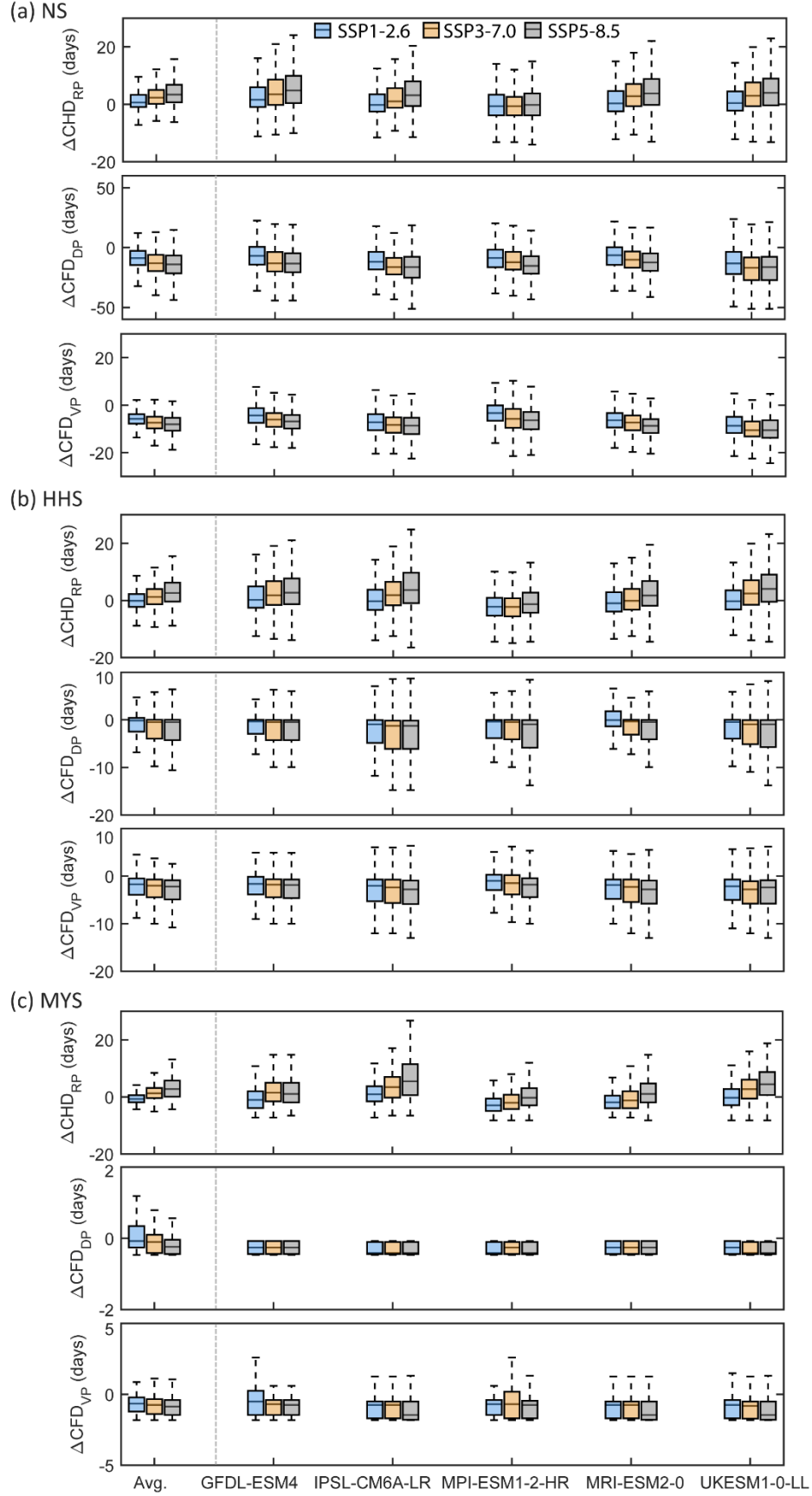


Fig. S4 Boxplot of projected changes (Δ) in compound hot-dry days (CHD) and compound freeze-dry days (CFD) during growth phases under three future climate scenarios (SSP1-2.6, SSP3-7.0, and SSP5-8.5). Boxplots indicate the median (horizontal line), 25-75th percentile (box), and 5-95th percentile (whiskers) of estimated changes in all year and location combinations for three sub-regions. GEP is the germination and establishment phase (planting to November); DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).

6. It is unclear in Fig. S3., which future SSP scenario is? In fact, the projected yield changes in each scenario are not shown. Are projected yield changes in future comparable to other studies?

Response: Thank you for pointing out this error. Original **Fig. S3** (now **Fig. S5**) is the future SSP5-8.5 scenario of ensemble average values of five climate models. We added the other two SSP1-2.6 and SSP3-7.0 scenarios in the Supplement in our revision. We also modified the description of the original **Fig. S3**, now read in Lines 239-240 in our revised Main.

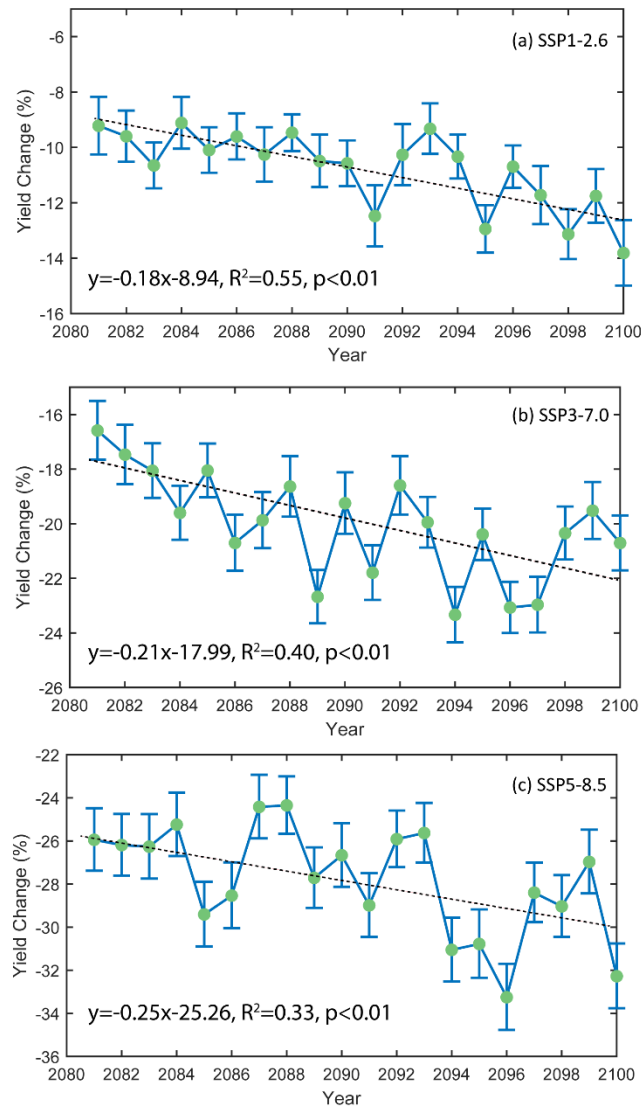


Fig. S5 Changes in average projected wheat yields in response to all extreme climate indices over time from 2080 to 2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios, respectively. The solid circles show estimated mean coefficients from the panel model; the error bars refer to a 95% confidence interval.

7. Results show consecutive dry days reduce in future climate, but do not consider extreme rainfall effects. Floods can reduce yield in this region as extreme climate events (e.g., Shi et al., 2021) and rainfall could become stronger under climate change, should discuss or/and include floods/extreme rainfall in analysis.

Shi, W., Wang, M., & Liu, Y. (2021). Crop yield and production responses to climate disasters in China. *Science of The Total Environment*, 750, 141147. <https://doi.org/10.1016/j.scitotenv.2020.141147>

Response: Thank you for the valuable comment. We fully agree that extreme rainfall and flooding are key factors that could impact crop yields under future climate conditions. In this study, we primarily focused on the effects of heat, freeze, dry, compound hot-dry, and compound freeze-dry climate events. Although we did not explicitly model the impacts of extreme rainfall events, we recognize that their frequency and intensity are projected to increase with climate change, which could pose additional risks to crop production. Therefore, we have added a discussion in the revised manuscript to acknowledge this limitation and highlight the need for future research to incorporate flood risks and extreme precipitation events into yield impact assessments.

The revised section, now reads in Lines 354-359:

“While our analysis focused on the effects of extreme climate events (heat, freeze, dry, and compound) on wheat yield, however, it is worth noting that crop damage from inundation or flooding was not considered. Given the rising precipitation variability and likelihood of more frequent and intense flooding events under future climate scenarios (Allan and Soden, 2008; Shi et al., 2021; Wang et al., 2017), the exclusion of flooding effects may lead to an optimistic estimate of climate-induced yield impacts.”

References:

- Allan, R. P., Soden, B. J., 2008. Atmospheric warming and the amplification of precipitation extremes. Science. 321, 1481-4.*
- Shi, W., et al., 2021. Crop yield and production responses to climate disasters in China. Science of the Total Environment. 750, 141147.*
- Wang, G., et al., 2017. The peak structure and future changes of the relationships between extreme precipitation and temperature. Nature Climate Change. 7, 268-274.*

End of Response for Reviewer 1.

Reviewer #2 (Remarks to the Author) for COMMSENV-25-0409:

I read this study on assessing extreme climate impacts on winter wheat yields. The authors provide valuable insights into regional wheat vulnerability through their modeling approach. While the manuscript makes significant contributions, I would like to highlight several points that require attention for additional analysis or discussions.

Response: Thank you for your in-depth suggestions and comments. We agreed with these points, and they substantially improved our paper. Please check our point-by-point response below.

1. The use of abbreviations in the abstract and the main text is problematic for readers. Consider spelling them out or finding alternative ways to improve clarity in your statements.

Response: We appreciate your suggestion. We tried our best to spell out the abbreviations and revised the Abstract as below:

Lines 30-41: “Extreme climate events (ECEs) pose significant threats to global food security, particularly impacting winter wheat yields in Northern China. Here, we examined both historical and projected effects of ECEs on wheat production across three sub-regions (North, Middle, and South). Using statistical models and cropping system simulations, we quantified yield losses driven by individual and compound stressors under historical (1999-2019) and future climate scenarios (2080-2100). Historically, post-anthesis compound hot-dry and spring heat stress caused the most yield reductions in the North and Middle sub-regions. Yet, compound freeze-dry events were the primary driver of yield loss in the South. By 2080-2100, the increase of post-anthesis compound hot-dry is projected to result in even greater yield reductions. Heat stress is expected to offset the benefits of reduced freeze stress, particularly in the cooler North sub-region where its effects are more pronounced than in the warmer South sub-region. These findings highlight the urgent need for region-specific adaptation strategies to sustain wheat production under climate change.”

Additionally, we thoroughly streamlined the Main text. Our revisions would enhance the clarity and readability of the article, making it easier to understand.

2. Throughout the manuscript, year ranges should use en-dashes rather than hyphens (e.g., "1999–2019" instead of "1999-2019") for proper typographical convention.

Response: Thank you. We used the year ranges by en-dashes and compound words by hyphen. We carefully checked all cases throughout the main text.

3. The authors study an important agricultural region in North China, but the characteristics of this region are introduced quite late in the manuscript (Figure 7?). An earlier description of the study area would provide necessary context for readers unfamiliar with Chinese agricultural regions.

Response: We agree. Accordingly, we moved this Figure into the description section (now **Fig. 1**). Please see Lines 110-116 in our revision.

Lines 110-116: “Winter wheat is a major crop in the Huang-Huai-Hai (HHH) Plain of China (**Fig. 1a**), contributing 21% of global food supplies (FAO, 2021) and 80% of China’s wheat production (Shi et al., 2024), making it important for both domestic and international food security. The HHH wheatbelt is characterized by variable climate conditions, featuring north-south gradients in both temperature and precipitation across the region. Average growing season temperatures in HHH had a warming trend occurring across the entire region over the past 40 years (**Fig. 1b**) but presented a declining trend in average total precipitation (**Fig. 1c**).”

References:

FAO, 2021. FAOSTAT. <http://www.fao.org/faostat/>.

Shi, W., Wang, M., Tao, F., Xu, X., Deng, X., Liu, L., Kong, X., Zuo, L., Lei, M., Shi, X., 2024. Wheat redistribution in Huang-Huai-Hai, China, could reduce groundwater depletion and environmental footprints without compromising production. *Communications Earth & Environment* 5, 380.

4. The rationale behind the simultaneous use of logarithmic transformation and time trend terms in Equation (1) needs further explanation. How does this combination help separate technological trends from climate effects?

Response: Thank you for this excellent question. In Equation (1), we apply a logarithmic transformation to wheat yields primarily to stabilize the variance and interpret coefficients in percentage terms, which is common in yield-climate regression models. The log transformation helps reduce the influence of outliers and allows climate effect coefficients to be interpreted as semi-elasticities. Terms t and t^2 characterize the county-specific quadratic time trends, which are used to capture unobserved, underlying temporal trends in yield that are not explained by climate variables. The simultaneous use of log-transformed yield and time trend terms allows extreme climate indices to affect yields proportionally and to account for non-climatic temporal changes in yield, which can be found in the details of prior studies (Zaveri and B. Lobell, 2019; Zhu et al., 2022).

Therefore, we rewrote one sentence and added one sentence to enhance this explanation as below:

Lines 458 to 461: “the transformed yields by logarithms are primarily to stabilize the variance and interpret coefficients in percentage terms as well as to improve residual distributions normality; terms t and t^2 characterize the county-specific nonlinear but progressive technology improvements over time, which are not explained by climate.”

References:

Zaveri, E., B. Lobell, D., 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. *Nature communications*. 10, 4144.

Zhu, P., et al., 2022. The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. *Nature Climate Change*. 12, 485-490.

5. The manuscript would benefit from addressing several methodological limitations. The temperature thresholds defining heat stress ($T_{max} \geq 30^{\circ} \text{C}$) and freeze stress require better

physiological justification specific to Chinese wheat varieties.

Response: Thank you for this insightful comment. We agree that physiological justification for the selected temperature thresholds is essential. In our study, heat stress was defined as maximum temperature ($T_{\max}$) $\geq 30^{\circ}\text{C}$ (denoted as T_h), with nearly all heat stress events occurring post-anthesis, consistent with the threshold reported in Liu et al. (2014). The review from Sánchez et al. (2014) on cardinal temperatures in wheat suggested that maximum temperatures are generally highest during grain filling (with an average of 35.4°C and 31°C for grain filling and anthesis), showing a wider range of cardinal temperatures than for anthesis. However, several studies have used around 30°C as the threshold temperature for wheat (Farooq et al., 2011; Porter and Gawith, 1999; Semenov et al., 2014), suggesting its physiological relevance.

Specifically for Chinese winter wheat, Liu et al. (2017) demonstrated that exposure to temperature $\geq 30^{\circ}\text{C}$ during the reproductive period led to a reduced leaf photosynthesis rate and biomass, supporting the appropriateness of this threshold. We have now clarified this rationale in our revision to strengthen the physiological basis for our definition of heat stress.

Lines 435-438: “For winter wheat in China, the temperature threshold of 30°C was appropriately used for heat stress, since heat stress over 30°C may result in reduced stomatal conductance and photosynthetic assimilation, which in turn led to a decline in grain yield formulation in Chinese winter wheat (Liu et al., 2017).”

For freeze injury stress, it is usually defined when the minimum temperature falls below a certain threshold value. We adopt different freeze stress thresholds during different growth phenology because diverse physiological processes have shown different tolerance in response to freeze stress (Liu et al., 2019). As shown in **Table S1**, we summarized the threshold of freeze injury temperature in each phenological phase for winter wheat based on other studies (Jiang et al., 2025; Porter and Gawith, 1999). Due to the varying monthly freeze thresholds, we categorized the growing season into four major physiological stages and assigned stage-specific temperature thresholds. These thresholds (-11°C for planting to anthesis, and -1°C for anthesis to maturity) were derived by aggregating monthly T_{frez} values reported in earlier work. We used -11°C as a conservative estimate reflecting hardening and pre-dormant tolerance. Similarly, we justified using -1°C to represent the freeze sensitivity of reproductive stages from anthesis to maturity, as Xiao et al. (2018) used a T_{frez} range of 0°C to -2°C to identify spring frost damage.

We revised the sentences for freeze definition and recited the references used for freeze injury in each phenological phase for winter wheat as below:

Lines 438-442: “Freeze (freeze days, FD) is the number of days when $T_{\min}$ is below T_{frez} during each of the four growth phases indicating freeze stress occurrence (FDD) (Zhang et al., 2022; Zhao et al., 2022). The T_{frez} selected represents the freeze injury thresholds associated with each growth phase of wheat in China based on previous studies (Jiang et al., 2025; Porter and Gawith, 1999), as detailed in **Table S1**.”

Table S1 The freezing growing temperature threshold (T_{frez} , $^{\circ}\text{C}$) in each phenological phase for winter wheat in our study and other research.

Jiang et al. (2025); (Porter and Gawith, 1999)			Our study	
Month	Growing stages	Tfrez (°C)	Categorized stage	Tfrez (°C)
Sep	Plant	0.0	Planting-November	-11.0
Oct	Vegetative	0.0		
Nov	Hardening	-5.0		
Dec	Dormant	-11.0	December-February	-11.0
Jan	Dormant	-11.0		
Feb	Dormant	-11.0		
Mar	Vegetative	-4.0	March-Anthesis	-1.0
Apr	Jointing	-4.0		
May	Heading	-1.0		
Jun	Filling	-2.2	Anthesis-Maturity	-1.0
Jul	Maturity	-2.2		

References:

- Farooq, M., et al., 2011. Heat stress in wheat during reproductive and grain-filling phases. *Critical Reviews in Plant Sciences*. 30, 491-507.
- Jiang, T., et al., 2025. Understanding the impacts of extreme temperature and humidity compounds on winter wheat traits in China. *Agricultural and Forest Meteorology*. 362, 110354.
- Liu, B., et al., 2014. Post-heading heat stress and yield impact in winter wheat of China. *Global change biology*. 20, 372-381.
- Liu, B., et al., 2017. Modelling the effects of post-heading heat stress on biomass growth of winter wheat. *Agricultural and Forest Meteorology*. 247, 476-490.
- Liu, L., et al., 2019. Response of biomass accumulation in wheat to low-temperature stress at jointing and booting stages. *Environmental and Experimental Botany*. 157, 46-57.
- Porter, J. R., Gawith, M., 1999. Temperatures and the growth and development of wheat: a review. *European journal of agronomy*. 10, 23-36.
- Sánchez, B., et al., 2014. Temperatures and the growth and development of maize and rice: a review. *Global change biology*. 20, 408-417.
- Semenov, M., et al., 2014. Adapting wheat in Europe for climate change. *Journal of cereal science*. 59, 245-256.
- Xiao, L., et al., 2018. Estimating spring frost and its impact on yield across winter wheat in China. *Agricultural and Forest Meteorology*. 260, 154-164.
- Zhang, T., et al., 2022. Climate change may outpace current wheat breeding yield improvements in North America. *Nature communications*. 13, 5591.
- Zhao, H., et al., 2022. U.S. winter wheat yield loss attributed to compound hot-dry-windy events. *Nature Communications*. 13, 7233.

6. While consecutive dry days serve as a drought indicator, actual soil moisture or antecedent precipitation might better represent plant water stress. It is necessary to incorporate soil moisture for the physiological relevance of drought stress characterization, especially during compound events.

Response: This is an important point. We agree and appreciate the reviewer's insightful comment. In our study, we used consecutive dry days (low precipitation) as a drought indicator because it is widely adopted in climate and agricultural research for capturing drought stress. A comprehensive assessment of compound hot-dry extremes based on different drought conditions (low precipitation or especially soil moisture) is necessary to fully understand the drought dynamics. However, in many regions, especially relatively large spatial or historical scales, high-resolution soil moisture data remains limited or unavailable, making consecutive dry days a practical choice. Critically, the response of soil moisture to climate warming is complicated by uncertainty over future changes in precipitation and its partitioning to soil moisture and evapotranspiration (Ault, 2020; Fowler et al., 2021; Scheff et al., 2021). Some studies found that crop responses to extreme heat thus tend to have countervailing effects on soil moisture (Lesk et al., 2022). Crops can cool themselves and the land surface through transpiration, limiting detrimental heat extremes (Mueller et al., 2017; Thiery et al., 2020). Yet in doing so they deplete soil moisture (Siebert et al., 2014). Therefore, elevated temperatures tend to occur with low soil moisture. Consequently, we believe that using consecutive dry days (low precipitation) serves as a meaningful indicator for compound events. Nevertheless, we acknowledge that we have limitations using compound hot-dry events, particularly when not accounting for soil properties, antecedent conditions, or evapotranspiration demand. In our future work, we would like to integrate different drought conditions (precipitation and soil moisture) to provide a more comprehensive assessment of drought stress. Therefore, we added the following sentences to the Discussion section as below:

Lines 360-368: “In addition, we used consecutive dry days to serve as a drought indicator to connect with heat stress for compound extreme hot-dry events. Low precipitation (consecutive dry days) has been widely adopted in drought assessments, and the use of compound heat-precipitation extreme events are relatively common in China (Lesk et al., 2022; Ning et al., 2022). However, the connections between water and heat climate extremes and their biological impacts on crops raise the potential for compound, interactive effects of changing precipitation, temperature, and soil moisture (Sarhadi et al., 2018; Zscheischler et al., 2020). Future studies should incorporate such complementary drought metrics to better capture the complexity of drought impacts on crop productivity.”

References:

- Ault, T. R., 2020. On the essentials of drought in a changing climate. *Science*. 368, 256-260.
- Fowler, H. J., et al., 2021. Anthropogenic intensification of short-duration rainfall extremes. *Nature Reviews Earth & Environment*. 2, 107-122.
- Lesk, C., et al., 2022. Compound heat and moisture extreme impacts on global crop yields under climate change. *Nature Reviews Earth & Environment*. 3, 872-889.
- Mueller, N. D., et al., 2017. Global relationships between cropland intensification and summer temperature extremes over the last 50 years. *Journal of Climate*. 30, 7505-7528.
- Ning, G., et al., 2022. Rising risks of compound extreme heat-precipitation events in China. *Int. J. Climatol*. 42, 5785-5795.
- Sarhadi, A., et al., 2018. Multidimensional risk in a nonstationary climate: Joint probability of increasingly severe warm and dry conditions. *Science advances*. 4, eaau3487.
- Scheff, J., et al., 2021. CO₂-plant effects do not account for the gap between dryness indices and projected dryness impacts in CMIP6 or CMIP5. *Environmental Research Letters*. 16, 034018.
- Siebert, S., et al., 2014. Impact of heat stress on crop yield—on the importance of considering

canopy temperature. Environmental Research Letters. 9, 044012.
Thiery, W., et al., 2020. Warming of hot extremes alleviated by expanding irrigation. Nature communications. 11, 290.
Zscheischler, J., et al., 2020. A typology of compound weather and climate events. Nature reviews earth & environment. 1, 333-347.

7. Perhaps here is a problematical issue: the analysis focuses exclusively on rainfed systems when irrigation is prevalent throughout Northern China's wheat production regions (as documented in Li et al., 2024 NPJ Climate and Atmosphere Sciences and Piyush et al., 2024, Nature Water). This critical oversight renders the findings largely irrelevant for real-world agricultural management and adaptation planning. The authors need to clarify this point.

Response: Thank you and we certainly agree with your suggestion. We limited reporting on rainfed production systems, although some of Northern China implements irrigation practices, irrigation would cool local air temperatures and buffer extreme heat (Lobell et al., 2008). Additionally, the resolved empirical relationship between yield and extreme heat is typically weakened when irrigated (Troy et al., 2015), with yield loss occurring at a higher temperature (Schauberger et al., 2017). Therefore, we clarified our analysis limitations as below:

Lines 368-376: “Our analysis has focused on the impact of extreme climate events on crop yields. We have focused exclusively on rainfed systems since irrigation would cool local air temperatures and buffer extreme heat effects (Lobell et al., 2008). However, this simplifies real-world heat stress responses as irrigation is practiced throughout Northern China's wheat production regions. The actual implementation of management and adaptation to alleviate extreme climate negative effects will require further consideration of irrigation in Northern China (Mehta et al., 2024). Future studies will need to account for the influence of extreme climate events on irrigated systems to comprehensively assess the implications of projected climate extremes for the entire Chinese wheat production system.”

References:

Lobell, D. B., et al., 2008. Irrigation cooling effect on temperature and heat index extremes. Geophysical Research Letters. 35.
Mehta, P., et al., 2024. Half of twenty-first century global irrigation expansion has been in water-stressed regions. Nature Water. 2, 254-261.
Schauberger, B., et al., 2017. Consistent negative response of US crops to high temperatures in observations and crop models. Nature communications. 8, 13931.
Troy, T. J., et al., 2015. The impact of climate extremes and irrigation on US crop yields. Environmental Research Letters. 10, 054013.

End of Response to Reviewer 2.

Reviewer #3 (Remarks to the Author) for COMMSENV-25-0409:

This is an interesting study focusing on the effects of weather extremes on wheat yield in Northern China. As weather shocks become increasingly important, I believe this research is an important step in understanding food security in the context of increasing weather variability.

Response: We greatly appreciate your encouraging comments and insight. We have revised and provided a point-by-point response as below.

My comments are as follows:

1. In Equation 1, the authors use multiple temperature accumulation indices to quantify chilling, hot, and compound weather extremes. I noticed that the phenology data they use are from agro-meteorological sites, which are not fixed each year. This raises concerns about potential issues, such as warmer temperatures causing shorter growing durations. For example, if you calculate temperature accumulation for a warmer climate, it might equate to a cooler climate but with a longer growing duration. Could this discrepancy affect the results?

Response: Thank you for your thoughtful and important comment. We agree the concern that year-to-year variation in phenological timing (especially earlier development under warming conditions) can influence the calculation of temperature-based indices, potential confounding thermal accumulation with phenology shifts.

To minimize this issue, we did not use year-specific phenological dates from agro-meteorological stations, which can vary substantially and are themselves influenced by temperature. Instead, we followed the widely used methodology of Sacks et al. (2010), applying average phenological dates for each site. This approach defines a consistent and climatologically representative growing period for each site, reducing potential endogeneity and allowing for meaningful comparisons of thermal accumulations across years and climates.

This approach helps smooth out interannual fluctuations and provides a representative growing season window that reflects typical crop development patterns. In addition, a fixed time window was often set for some temperature accumulation indices in climate impact studies (e.g., Lobell et al., 2011; Lobell et al., 2012), rather than the growing season of each individual year. Part of doing this is because the latter would result in endogeneity in an analysis of FDD, GDD, and EDD on yields (e.g., warmer seasons may not have higher GDD than shorter growing seasons).

References:

- Sacks, W. J., et al., 2010. Crop planting dates: an analysis of global patterns. *Global ecology and biogeography*. 19, 607-620.
- Lobell, D. B., et al., 2011. Nonlinear heat effects on African maize as evidenced by historical yield trials. *Nature climate change*. 1, 42-45.
- Lobell, D. B., et al., 2012. Extreme heat effects on wheat senescence in India. *Nature Climate Change*. 2, 186-189.

2. Lines 398–409 mention that the wheat yield data cover the period from 1999 to 2019, while the phenology data span from 1992 to 2013. Why not align these periods to ensure consistency?

Response: We thank you for your comments and suggestions. Yes, we tried to collect and align the length of these two datasets to ensure consistency, however, since most statistical yearbooks from the National Bureau of Statistics (<http://data.cnki.net/>) do not provide winter wheat yields and production data before 1999, and we want to keep the data as long as possible to compare them with future data, therefore these data only cover from 1999 to 2019. Additionally, we collected phenological data from 1992 to 2013 for 90 agrometeorological stations operated by the China Meteorological Administration (CMA, <http://data.cma.cn/en>) because the data for these years are relatively complete and consistent (Chen et al., 2020). Only a small subset of sites recorded phenology data beyond this scope, so we omit this small fraction of the data.

References:

Chen, X., et al., 2020. *Impacts of multi-timescale SPEI and SMDI variations on winter wheat yields. Agricultural Systems.* 185, 102955.

3. It is common for hot days (HD) to have higher EDD and CHD. I suggest that the authors include a co-linearity analysis in the supplementary file to address this.

Response: In our study, HD, EDD, and CHD represent different mechanisms affecting crop physiology. HD reflects the frequency of daily maximum temperatures, EDD quantifies the cumulative thermal stress by summing the intensity of heat, and CHD identifies days when both high temperature and low precipitation occur together, emphasizing compound climate extremes. While some degree of correlation is expected due to their shared components, their distinct climatological meanings justify their inclusion.

Based on your suggestion, we added a co-linearity analysis as **Table S5**:

Table S5. Co-linearity analysis of climate variables

Variables	VIF
HD	9.612
EDD	4.4598
CHD	8.7558

VIF values for each variable remained below 10, suggesting that while multicollinearity exists, it is within acceptable levels for regression analysis (Doetterl et al., 2015; Wang et al., 2022).

References:

Doetterl, S., et al., 2015. *Soil carbon storage controlled by interactions between geochemistry and climate. Nature Geoscience.* 8, 780-783.

Wang, T., et al., 2022. *Impact of climate variability on grain yields of spring and summer maize. Computers and Electronics in Agriculture.* 199, 107101.

4. I recommend moving the section titled “Response of Wheat Yield to Extreme Climate Indices” to the beginning of the paper. This is likely the most interesting thing for readers and should be prioritized.

Response: We agree. We have moved the “Response of Wheat Yield to Extreme Climate Indices” to the beginning of the manuscript. Please check Lines 136-173 highlighted in yellow in our revision.

6. I also suggest adding a table in the main text to show the response coefficients and standard deviations. This would allow readers to quickly identify the most impactful phases and key climate factors affecting wheat yields.

Response: Thank you for your nice comments. We added a table to show the regression coefficients and standard errors. In our study, we focused on how changes in extreme climate events affect yields. Therefore, we only reported the regression coefficients of extreme climate indices in the table. Since the content of this table overlaps **Fig. 3** in the Main text, we moved it to the Supplement.

Table S4 Impact of extreme climate indices on wheat yield

Climate indices	NS	HHS	MYS
EDD _{VP}	-0.064 (0.003)	-0.035 (0.002)	-0.028 (0.001)
EDD _{RP}	-0.021 (0.001)	-0.010 (0.001)	-0.014 (0.001)
FDD _{DP}	-0.003 (0.003)	0.002 (0.001)	0.022 (0.001)
FDD _{VP}	-0.018 (0.001)	0.001 (0.001)	-0.046 (0.006)
CDD _{DP}	-0.002 (0.001)	0.002 (0.000)	0.000 (0.001)
CDD _{VP}	-0.012 (0.001)	0.001 (0.001)	0.017 (0.001)
CDD _{RP}	-0.003 (0.002)	0.001 (0.001)	0.006 (0.002)
CHD _{RP}	-0.075 (0.004)	-0.040 (0.002)	0.001 (0.002)
CFD _{DP}	0.020 (0.002)	-0.027 (0.002)	-0.124 (0.002)
CFD _{VP}	-0.004 (0.003)	-0.003 (0.003)	-0.031 (0.001)

Notes: Dependent variable is the logarithm of wheat yield. Each column represents a regression model for each sub-region (NS, the North; HHS, the Middle; MYS, the South). Standard errors are displayed in parentheses.

7. There is a significant difference between statistical models and process-based models in assessing the impacts of weather extremes. While I agree that some impact processes may not be incorporated into the models, the current discussion on this topic seems disconnected from the conclusions. I did not find a focused discussion on this result in the subsequent sections. Therefore,

I recommend either removing the results related to process-based models or adding more discussions to better integrate this results into the paper.

Response: We appreciate you for bringing up this point and agree that it is important. We have revised and enhanced the Discussion section to address the contrasting sensitivities shown by the two approaches. We also strengthened the connections between statistical models and process-based models with broader conclusions in terms of climate impacts. Please see Lines 309-329 in our revised manuscript:

Lines 309-316: “Additionally, we observed that the statistical model tended to predict less negative yield response to temperature extremes than the process-based model. One potential explanation is that statistical models reflect aggregate outcomes across diverse environments, and Northern China is characterized by relatively lower humidity so that it may experience greater evaporative cooling under warming conditions. Therefore, this would reduce heat impacts (Gourdji et al., 2013). However, this does not necessarily imply the statistical model performed greater accuracy, as the statistical model also captures interactions between temperature and humidity.”

Lines 317-329: “Our comparison of yield sensitivities to precipitation extremes revealed additional discrepancies. The process-based model simulated greater yield losses from drought stress during the vegetative stage than during the reproductive stage. In contrast, the statistical model indicated that drought during the reproductive phase had a stronger negative effect on observed yields (**Fig. 6g**). This divergence is consistent with earlier findings (Lobell and Asseng, 2017), which showed that process-based and statistical models often differ in their estimated precipitation sensitivities. This may be due to the fact that process-based models operate with fixed soil parameters (Asseng et al., 2011) and assumed initial soil water conditions (Moeller et al., 2009), while the statistical models aggregated across a wide range of field conditions and soil types. Moreover, process-based models may empirically overemphasize the role of precipitation (Eitzinger et al., 2004) while overlooking other field-level constraints, such as heavy precipitation within a short time, waterlogging, or lodging. These limitations highlight the value of combining both modeling approaches and point to the need for further study to clarify the underlying causes of divergence.”

References:

- Asseng, S., et al., 2011. The impact of temperature variability on wheat yields. Global Change Biology. 17, 997-1012.*
- Eitzinger, J., et al., 2004. Comparison of CERES, WOFOST and SWAP models in simulating soil water content during growing season under different soil conditions. Ecological modelling. 171, 223-246.*
- Gourdji, S. M., et al., 2013. An assessment of wheat yield sensitivity and breeding gains in hot environments. Proceedings of the Royal Society B: Biological Sciences. 280, 20122190.*
- Lobell, D. B., Asseng, S., 2017. Comparing estimates of climate change impacts from process-based and statistical crop models. Environmental Research Letters. 12, 015001.*
- Moeller, C., et al., 2009. Plant available soil water at sowing in Mediterranean environments—Is*

it a useful criterion to aid nitrogen fertiliser and sowing decisions? Field Crops Research. 114, 127-136.

End of Response to Reviewer 3

Point-by-point Responses to Three Reviewers for COMMSENV-25-0409A

We greatly appreciate these insightful comments and suggestions to our manuscript. The following pages contain our point-by-point responses to Reviewers' comments. Reviewer's comments are shown in regular fonts, our responses are in **blue fonts**, and revised manuscript text is highlighted in **red fonts**. Also, our revision has been highlighted by yellow in the Main text.

Reviewer #1 (Remarks to the Author) for COMMSENV-25-0409A:

While the authors have addressed some issues, there are still concerns.

Response: We appreciate your encouraging review. Your comments and suggestions substantially improved the quality of this study. Please check our point-by-point response.

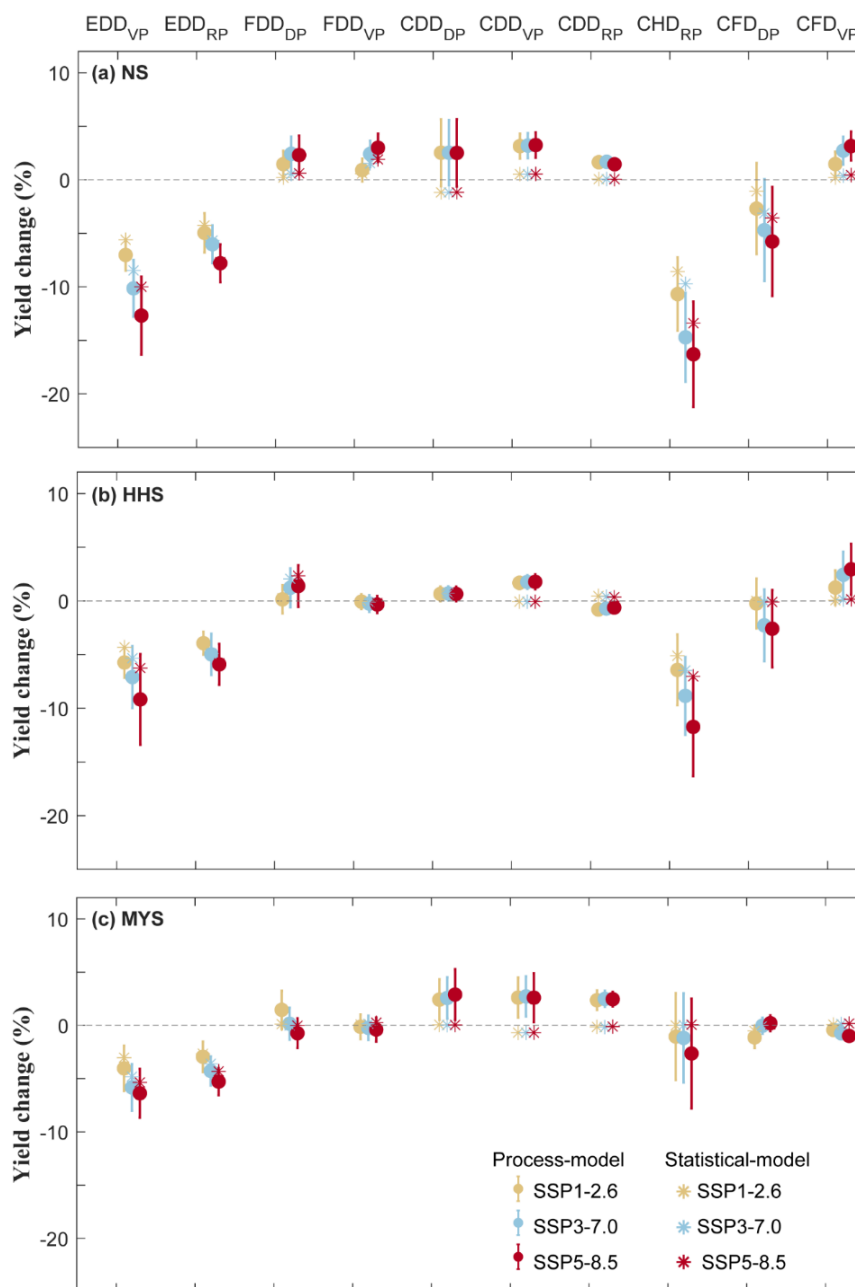
*Regarding my comment #4, lines 234-236: These sentences do not appear to be correct in the manuscript. There was no good agreement between observed and simulated yield responses in most panels in figure 6. The authors acknowledge in their response that the apparent differences in yield sensitivity across the panels reflect fundamental distinctions between the statistical and process-based modeling frameworks. Therefore, the projected climate-driven changes in winter wheat yield can be biased using only a process-based model. Therefore, I suggested using both methods for future climate change effects or making some corrections using observations.

Response: Thanks for your careful review and insightful comments. Yes, in our study, we used two approaches to address yield responses as you suggested. Firstly, we used extreme climate predictors derived from the future climate general circulation models data (GCMs), then our regression equation was used to fit to these predictors and yield statistics. Then, the estimated regressed coefficients were compared to the estimated coefficients using the process-based simulated yield. A similar method can be found in Zhu et al. (2022). We agree that the differences in the yield sensitivity response reflect distinctions between these two approaches. Accordingly, to address your concern and question, we updated **Fig.7** and revised relevant descriptions in the revised text.

Updated **Fig. 7** in our revision as below:

Fig. 7. Impact of extreme climate indices on wheat yields by 2080-2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios.

Estimated effects of future changes in extreme climate indices on wheat yields, derived from both the process-based and statistical models for the (a) north (NS), (b) middle (Huang-Huai, HHS), and (c) south (middle-lower reaches of Yangzi River, MYS) sub-regions. Extreme climate indices are extreme degree days (EDD), freezing degree days (FDD), consecutive dry days (CDD), compound hot-dry days (CHD), and compound freeze-dry days (CFD). The vertical bars indicate the 95% confidence interval of the average value (solid dots). DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).



The relevant description has also been revised as:

Lines 238-253: “Across the HHH, future ECEs would consistently lead to reductions in wheat yield (**Fig. 7**). The comparison of the negative extreme climate effects estimated with the process-based simulated yields and yield statistics reveal that the statistics models do not reproduce the process model-derived negative response of yield to extreme climate events. For yield changes due to heat stress (EDD) and compound hot-dry extremes (CHD), statistical models generally reproduce the directions of yield change, but the magnitudes of yield change were smaller than estimated from the process-based model, with the largest discrepancies observed in the NS. The ensemble mean of EDD effects suggests that by 2080–2100, warmer climate results in yield declines of $5.6 \pm 1.5\%$ (SSP1-2.6), $7.7 \pm 2.2\%$ (SSP3-7.0), and $9.4 \pm 3.2\%$ (SSP5-8.5) primarily due to temperature stress in spring (EDD_{VP}). However, such yield decline would likely be offset by yield benefits due to reduced exposure to freezing stress in the MYS. Future warming is projected to lead to declines in drought exposure and reduced drought effect. However, future warming would lead to an increase in compound hot-dry events during the reproductive growth phase (CHD_{RP}) primarily driven by substantially rising heat stress thereby reducing yields. This effect would decrease future wheat yield more in the NS than HHS and MYS sub-regions, and these declining yields were greater as the climate scenarios increased in intensity.”

References:

Zhu, P., Kim, T., Jin, Z., Lin, C., Wang, X., Ciais, P., Mueller, N.D., Aghakouchak, A., Huang, J., Mulla, D., 2022. The critical benefits of snowpack insulation and snowmelt for winter wheat productivity. *Nature Climate Change* 12, 485-490.

*Regarding my comment #2, I agree with the other review that irrigation not being considered in the analysis is a big issue. Could you clarify whether these calibrated stations are irrigated? Do winter wheat yields, planted areas, and production data from the National Bureau of Statistics come from irrigated/rainfed areas or both?

Response: Thank you for raising this important point. In our study, the winter wheat yield, planting area, and production data from the National Bureau of Statistics (NBS) does not distinguish between irrigated and rainfed fields. These statistics are reported at the county or province level and represent aggregated outcomes of mixed production systems without disaggregation by irrigation status.

To address your and Reviewer #2 suggestions, we added irrigation data by using the share of wheat cropped area that is irrigated as a measure of wheat irrigation in our study. We incorporated the irrigation share (I, defined as the proportion of wheat-harvested area that is irrigated) as a control variable in our regression models to test the robustness of our results.

Accordingly, we used the MIRCA-OS dataset, which provides the global gridded data set of annual harvested areas for rainfed and irrigated wheat areas, with a resolution of 5 arc minutes for the years 2000 to 2015. We interpolated these data to the site level to compute irrigation share at each location. The average irrigation shares for 2000 to 2015 are also included in the Supplementary material (**Fig. S5**). As the resolution of 5 arc minutes of MIRCA-OS data is relatively high from the available dataset, the interpolated irrigation share is robust. Given the lack of post-2015

irrigation data, we assumed that irrigation share remained constant beyond 2015. This assumption is supported by recent literature indicating that although irrigated wheat area may have declined regionally due to groundwater constraints, the spatial distribution of irrigation intensity remains relatively stable (Li and Lei, 2021).

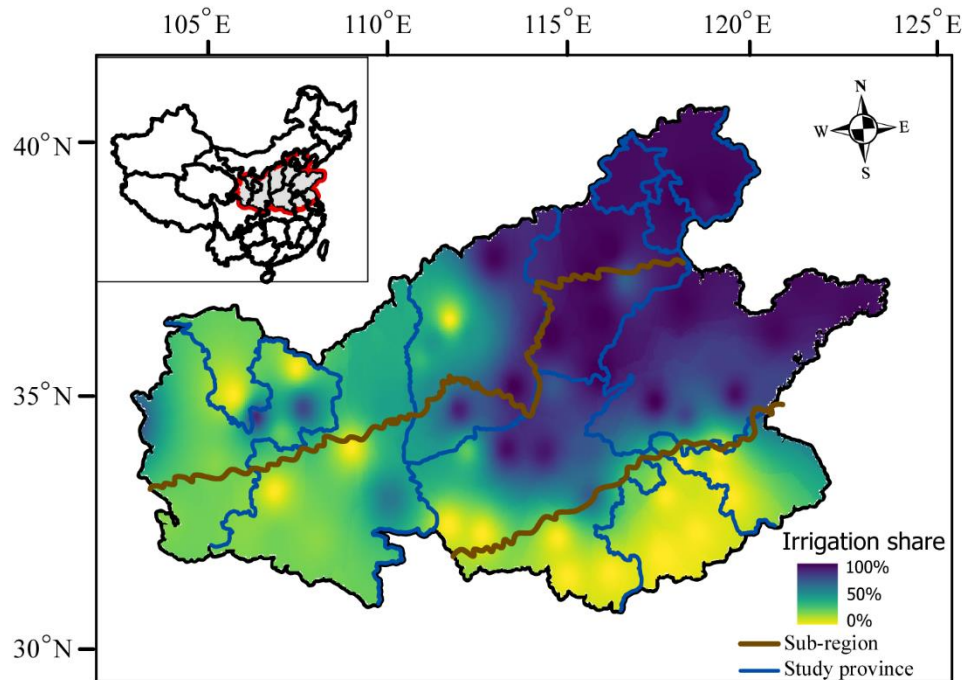


Fig. S5. Spatial distribution of averaged irrigation share (wheat irrigated area, % of wheat area) for 2000 to 2015 from the MIRCA-OS dataset in our study region.

Additionally, we added a description of the MIRCA-OS dataset in our revision as:

Lines 411-418: “Data for the rainfed and irrigated areas sown with winter wheat for the years 2000 to 2015, with a resolution of 5 arc minutes were obtained from the global gridded dataset of annual harvested areas for the 21st century (MIRCA-OS) (Kebede et al., 2025). We finely interpolated grid data to the site-level to compute irrigation share at each location. The average irrigation shares for 2000 to 2015 are shown in **Fig. S5**. Here, the total harvested area of winter wheat was calculated as the sum of the irrigated and rainfed wheat areas. The irrigation share (I) was then the irrigated area divided by the total harvested area at each site. Due to the absence of irrigation data, we assumed no change in irrigation share since 2015.”

Accordingly, we revised our Equation 1 to include irrigation share (I) as a covariate. This enables us to examine whether and how irrigation moderates the sensitivity of wheat yields to extreme climate stressors such as EDD and CDD.

The updated equation 1 in our revision is as below:

$$\text{Log Yield}_{d,t} = \sum_{j=2}^3 \beta_{1,j} \text{FDD}_{d,t}^j + \sum_{j=3}^4 \beta_{2,j} \text{EDD}_{d,t}^j + \sum_{j=2}^4 \beta_{3,j} \text{CDD}_{d,t}^j + \beta_4 \text{CHD}_{d,t} + \sum_{j=2}^3 \beta_{5,j} \text{CFD}_{d,t}^j + \beta_6 I_{d,t} + \alpha_d + \beta_{7,d} t + \beta_{8,d} t^2 + \varepsilon_{d,t} \quad (1)$$

Moreover, we added some sentences in Lines 451-455:

“Since wheat statistical yield data in our study region does not provide information on irrigated and rainfed yields separately, we are unable to directly estimate the impact of weather on each type. Therefore, to measure the change in sensitivity of yields to weather, we include the share of wheat-specific irrigated area ($I_{d,t}$), which we use as our measure of wheat irrigation (Zaveri and Lobell, 2019).”

Regarding the representativeness of our calibrated meteorological stations and yield datasets, we included both irrigated and rainfed sites, reflecting the heterogeneous agricultural practices. For example, in the northern North China Plain, stations such as Luancheng and Taian are associated with irrigated wheat systems, as supported by the MIRCA-OS dataset, while those in the southern North China Plain correspond predominantly to rainfed systems, consistent with regional management practices.

Accordingly, our process-based simulations were designed to incorporate irrigation management. Specifically, we used the automatic irrigation setting within the process-based model to approximate actual field practices (Chen et al., 2018). That is, wheat crop yields were simulated based on actual irrigation management practices. We set automatic irrigation as crop water demand required because of the spatially heterogeneous nature of irrigation across the region, driven by the dominance of smallholder farming in China (Li and Lei, 2021). From previous studies, irrigation in our study area varies substantially across provinces, within counties, and even among neighboring plots (Zhao et al., 2023). In general, northern North China Plain regions are more reliant on irrigation, while the southern North China Plain tends to be rainfed (Xiao and Tao, 2014; Zhao et al., 2023).

Therefore, we added some sentences in Lines 477-480 for our process-based model simulation:

“Here, irrigation was considered during model simulation. Given the spatially heterogeneous nature of irrigation across the region, the automatic irrigation setting within the model was used to approximate actual field practices. That is, wheat crop yields were simulated based on actual irrigation management practices.”

In addition, we conducted a comparative analysis using models with and without irrigation share as a control variable (see **Figs. R1-R2** below). While the direction of the estimated effects of extreme degree days (EDD) on yield remained consistent, the effect sizes were moderately larger in models that included irrigation, suggesting that excluding irrigation may lead to a lower climate sensitivity. A similar pattern was observed for consecutive dry days (CDD). These findings are consistent with the results by Zaveri and Lobell (2019), who noted that models without irrigation controls tend to yield lower-bound estimates. Therefore, we are confident that our results are robust and reflective of both irrigated and rainfed wheat systems.

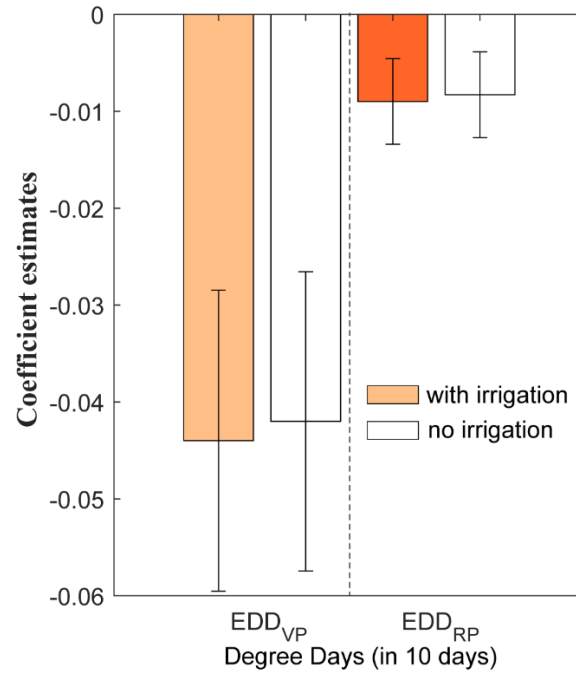


Fig. R1. Impacts of EDD_{VP} and EDD_{RP} on log wheat yield with and without irrigation controls.

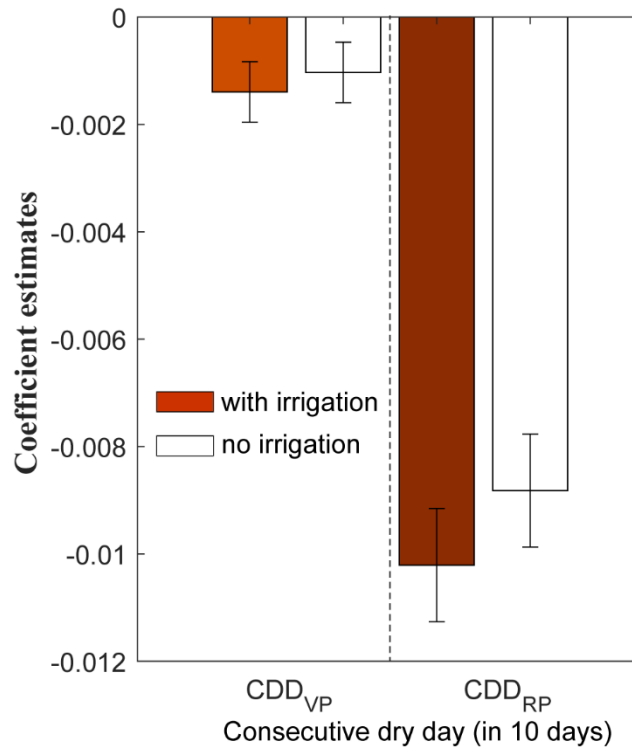


Fig. R2. Impacts of CDD_{VP} and CDD_{RP} on log wheat yield with and without irrigation controls.

Therefore, we added the following sentences to the Discussion section as below:

Lines 329-337: “It should be noted that our analysis explicitly incorporates irrigation, as it might influence local microclimates and regional climate patterns by altering land–atmosphere feedbacks and atmospheric moisture transport (Greve et al., 2025; Li et al., 2023). We included irrigation share as a covariate in our statistical models. We find that the estimated impacts of EDD and CDD on yield generally remain consistent in the same direction (i.e., negative impact) but are slightly larger in magnitude when irrigation is included, suggesting that omitting irrigation may lead to an underestimation of climate sensitivity. This finding is consistent with Zaveri and Lobell (2019), emphasizing that models excluding irrigation effects tend to provide lower-bound estimates of heat sensitivity.”

Additionally, we revised **Figs. 1-3** and **Fig. 6 (see below)** and their descriptions (lines 137-173 and lines 220-235) based on updated results as we added irrigation practices.

Fig. 1 Characterization of the study region.

(a) Winter wheat planting patterns (green background map) across each sub-region (north (NS); middle (Huang-Huai, HHS); south (middle-lower reaches of Yangzi River, MYS)). Circles are meteorological observations at irrigated (blue) and rainfed (orange) sites, and red stars indicate locations of experimental sites. (b) Average temperature and (c) Average total precipitation during the winter wheat growing season from 1980 to 2019.

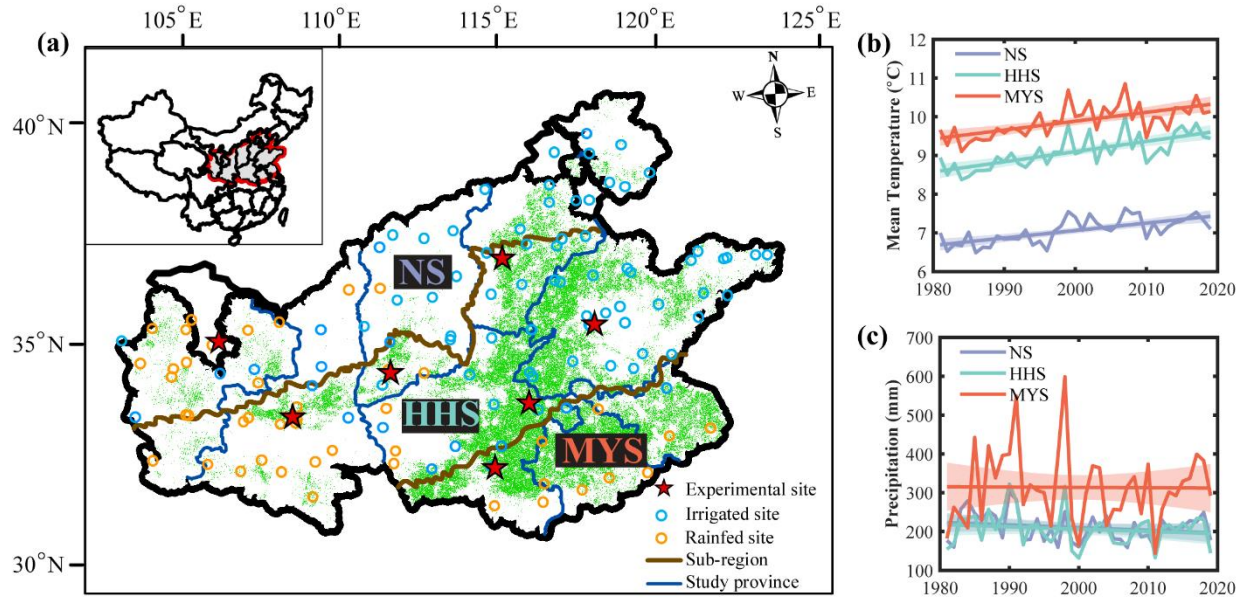


Fig. 2 Impacts of extreme climate indices on wheat yields.

(a) Sensitivity of winter wheat yields to extreme degree days (EDD) and freezing degree days (FDD) in different phenological phases; the error bars refer to 95% confidence intervals. (b) The percent change in yield as a function of the consecutive dry days (CDD) by different growth phases; shaded areas indicate the 95% confidence intervals while histograms show the distribution of CDD occurrence amounts sampled. (c) Changes in sensitivity of wheat yields to all extreme climate indices from 2000 to 2009 (blue shaded) and 2010 to 2019 (pink shaded). The solid circles show estimated mean coefficients from the statistical model; the error bars indicate the 95% confidence intervals.

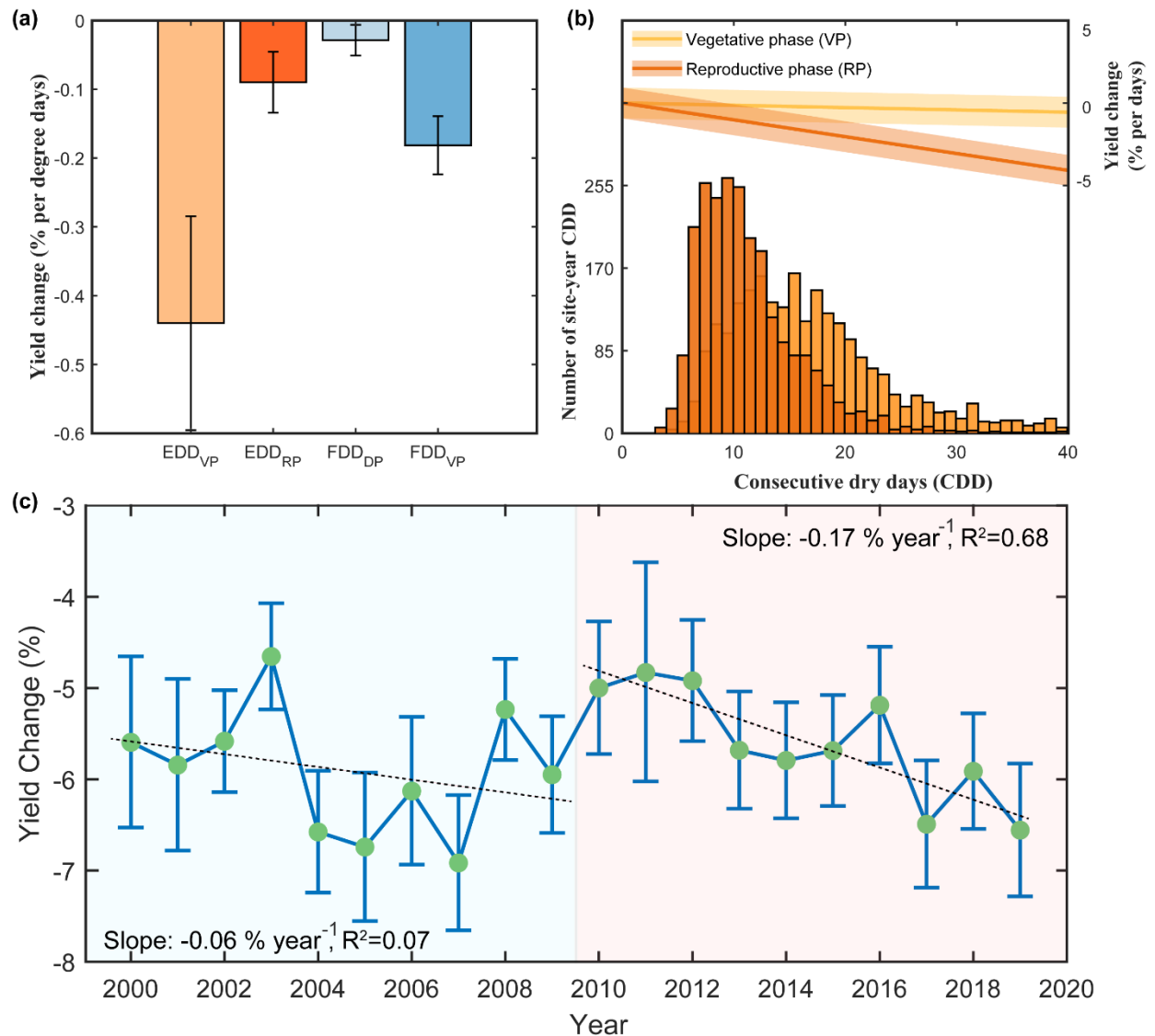


Fig. 3 Impacts of extreme climate indices on wheat yields at three sub-regions.

Yield changes due to extreme climate indices in the (a) north (NS), (b) middle (Huang-Huai, HHS), and (c) south (middle-lower reaches of Yangzi River, MYS) sub-regions. Extreme climate indices are extreme degree days (EDD), freezing degree days (FDD), consecutive dry days (CDD), compound hot-dry days (CHD), and compound freeze-dry days (CFD). The horizontal bars indicate the 95% confidence interval of the average value (solid dots). DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).

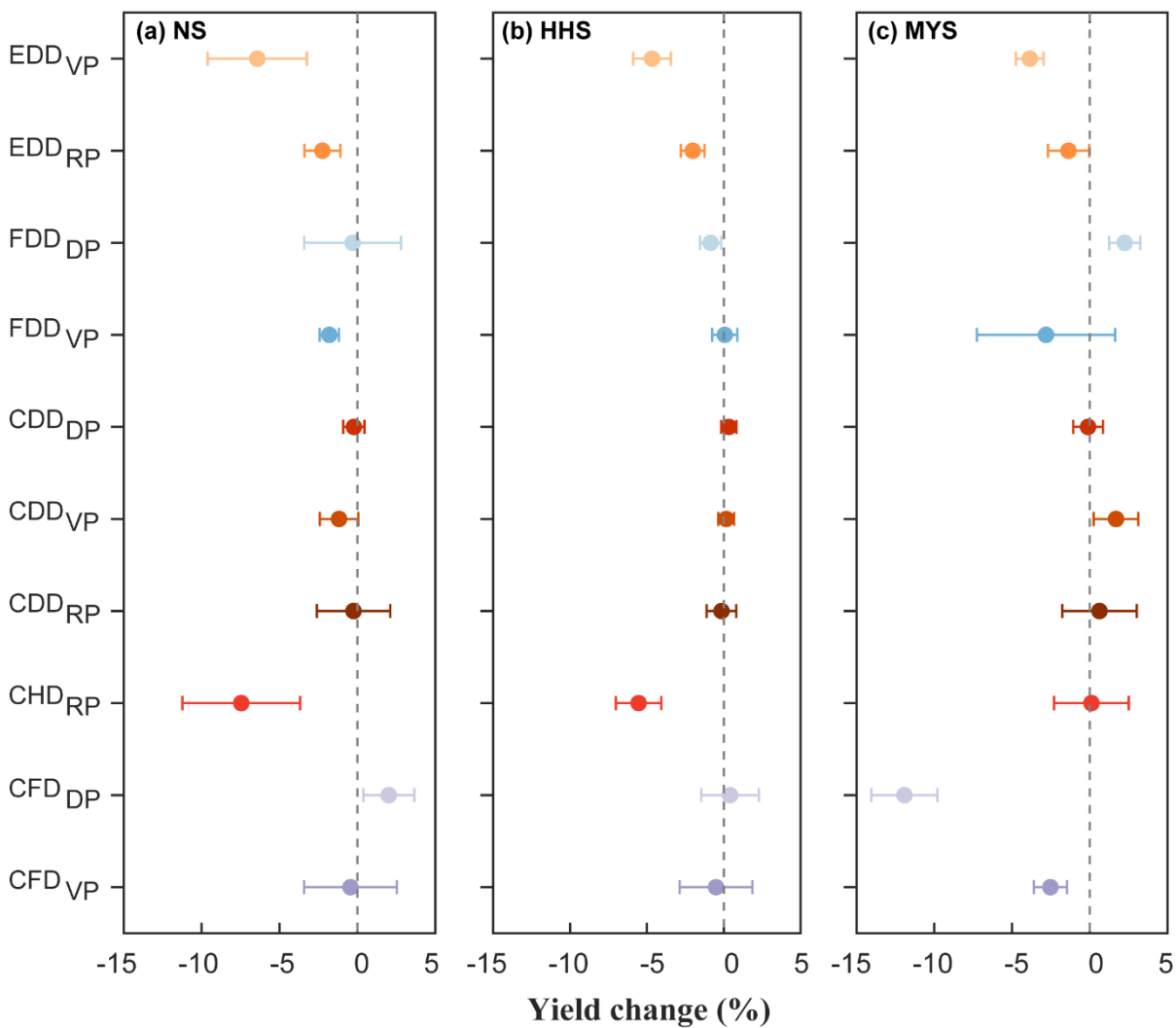
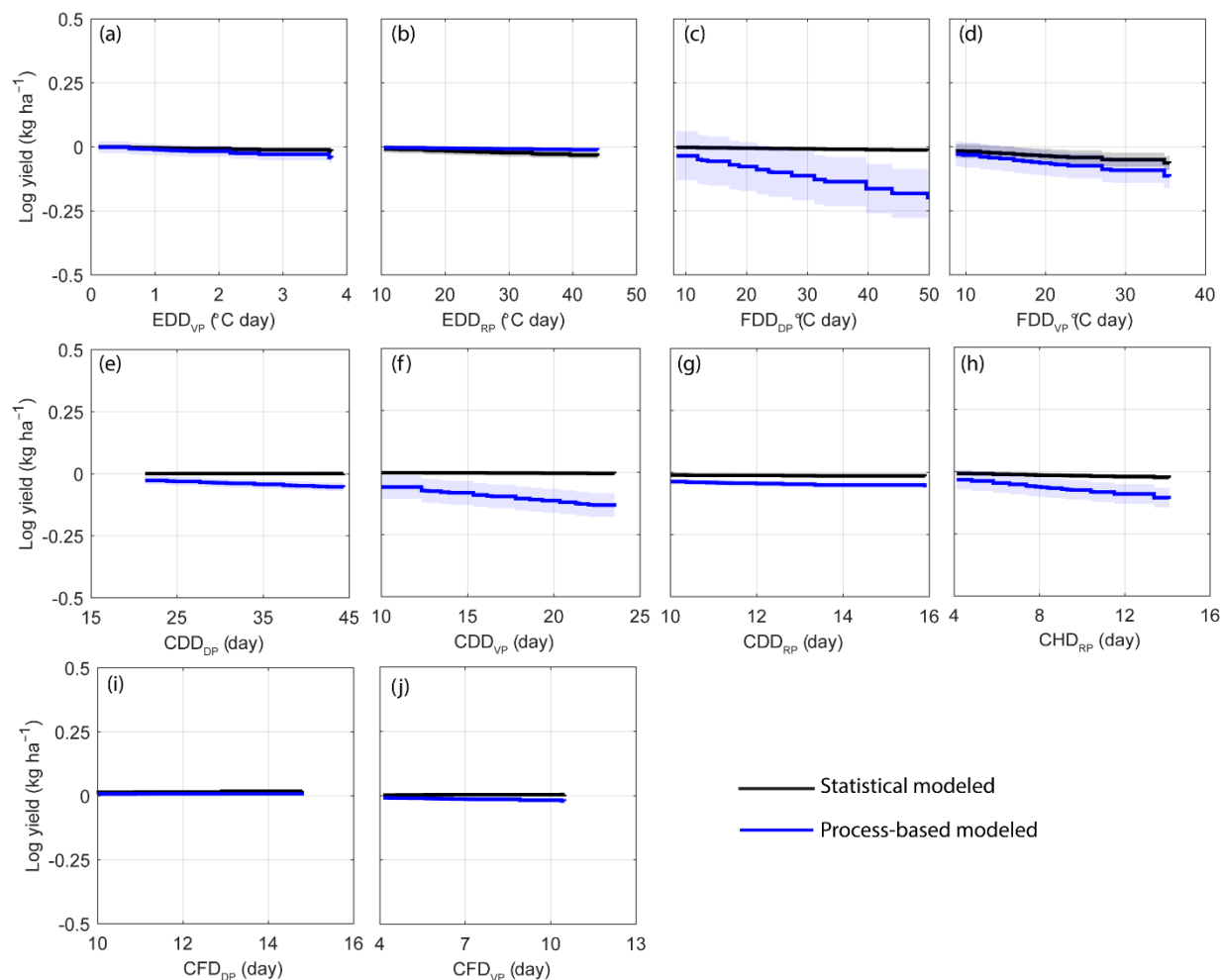


Fig. 6 Comparison of estimated effects of extreme climate indices on wheat yields.

Yield changes based on the process-based crop model and statistical model under (a-b) extreme degree days (EDD), (c-d) freezing degree days (FDD), (e-g) consecutive dry days (CDD), (h) compound hot-dry days (CHD), and (i-j) compound freeze-dry days (CFD). Black lines and blue lines are statistical modeling and process-based modeling, respectively. DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).



References:

- Chen, Y., Zhang, Z., Tao, F., 2018. Impacts of climate change and climate extremes on major crops productivity in China at a global warming of 1.5 and 2.0 C. *Earth System Dynamics* 9, 543-562.
- Greve, P., Schmitt, A.U., Miralles, D.G., McDermid, S., Findell, K.L., García-García, A., Peng, J., 2025. Observational evidence of increased afternoon rainfall downwind of irrigated areas. *Nat. Commun.* 16, 3415.
- Kebede, E.A., Oluoch, K.O.A. Siebert, S., Mehta, P., Hartman, S., Jägermeyr, J., Ray, D., Ali, T., Brauman, K.A., Deng, Q., 2025. A global open-source dataset of monthly irrigated and rainfed cropped areas (MIRCA-OS) for the 21st century. *Scientific Data* 12, 208.
- Li, H., Keune, J., Smessaert, F., Nieto, R., Gimeno, L., Miralles, D.G., 2023. Land–atmosphere feedbacks contribute to crop failure in global rainfed breadbaskets. *npj Climate and Atmospheric Science* 6, 51.
- Li, J., Lei, H., 2021. Tracking the spatio-temporal change of planting area of winter wheat-summer maize cropping system in the North China Plain during 2001–2018. *Comput. Electron. Agric.* 187, 106222.
- Xiao, D., Tao, F., 2014. Contributions of cultivars, management and climate change to winter wheat yield in the North China Plain in the past three decades. *Eur. J. Agron.* 52, 112-122.
- Zaveri, E., Lobell, D.B., 2019. The role of irrigation in changing wheat yields and heat sensitivity in India. *Nat. Commun.* 10, 4144.
- Zhao, Y., Tao, H., He, P., Yao, X., Cheng, T., Zhu, Y., Cao, W., Tian, Y., 2023. Annual 30 m winter wheat yield mapping in the Huang-Huai-Hai plain using crop growth model and long-term satellite images. *Comput. Electron. Agric.* 214, 108335.

End of Response for Reviewer 1.

Reviewer #2 (Remarks to the Author) for COMMSENV-25-0409A:

The authors have addressed some of my technical concerns adequately, particularly the temperature threshold justifications and drought indicator limitations.

However, my main concern about the irrigation issue remains unresolved. Beyond the local cooling effects that the authors mention, irrigation has significant regional and continental-scale impacts on water and energy transport (or downwind impacts, see REFs below). These feedbacks may largely influence the rainfed croplands' climate, such as the extensive irrigation region under this study.

The authors acknowledge that "irrigation is practiced throughout Northern China's wheat production regions" but continue to focus exclusively on rainfed systems. This creates a disconnect because the climate data they use to drive their (statistical) models may already reflect the influence of widespread irrigation on regional climate patterns. In essence, they may be applying "irrigated climate" to simulate "rainfed crops," which could lead to biased estimates of climate sensitivity.

I suggest the authors incorporate the irrigation fraction (in the plot or on the regional scale) as a control variable to validate their current results and findings. Probably, I can see the mitigating effects of irrigation on temperature and drought, particularly in summer.

Some papers about water and heat transport or downwind impacts of irrigations:

Li, H., Keune, J., Smessaert, F., Nieto, R., Gimeno, L. and Miralles, D.G., 2023. Land–atmosphere feedbacks contribute to crop failure in global rainfed breadbaskets. *npj Climate and Atmospheric Science*, 6(1), p.51.

Greve, P., Schmitt, A.U., Miralles, D.G., McDermid, S., Findell, K.L., García-García, A. and Peng, J., 2025. Observational evidence of increased afternoon rainfall downwind of irrigated areas. *Nature Communications*, 16(1), p.3415.

Response: We thank you for raising this important point and fully agree that irrigation can have significant regional and even continental-scale climate impacts, including alterations in energy and water transport that may influence downwind or nearby rainfed systems. Therefore, we incorporated the irrigation share (I, defined as the proportion of wheat-harvested area that is irrigated) as a control variable in our models.

However, there is no public dataset on the irrigated wheat area in the statistical yearbook released by the National Bureau of Statistics of China. The annual irrigated cropland area is only documented but the explicit information about its location and distribution is absent. Thus, we used the MIRCA-OS dataset, which provides the global gridded data set of annual harvested areas for rainfed and irrigated wheat areas, with a resolution of 5 arc minutes for the years 2000 to 2015. We interpolated these data to the site level to compute irrigation share at each site level. The average irrigation shares for 2000 to 2015 are also included in the Supplementary material (**Fig. S5**). As the resolution of 5 arc minutes of MIRCA-OS data is relatively high from the available dataset, the interpolated irrigation share is robust. Given the lack of post-2015 irrigation data, we assumed that irrigation share remained constant beyond 2015. This assumption is supported by

recent literature indicating that although irrigated wheat area may have declined regionally due to groundwater constraints, the spatial distribution of irrigation intensity remains relatively stable (Li and Lei, 2021).

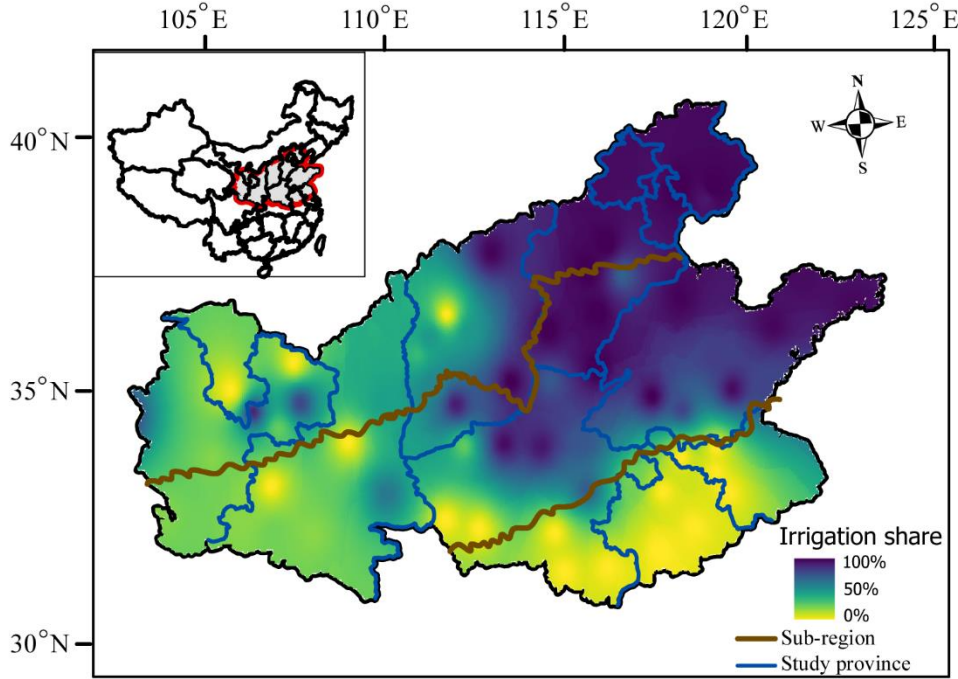


Fig. S5. Spatial distribution of averaged irrigation share (wheat irrigated area, % of wheat area) for 2000 to 2015 from the MIRCA-OS dataset in our study region.

Additionally, we added a description of the MIRCA-OS dataset in our revision as:

Lines 411-418: “Data for the rainfed and irrigated areas sown with winter wheat for the years 2000 to 2015, with a resolution of 5 arc minutes were obtained from the global gridded dataset of annual harvested areas for the 21st century (MIRCA-OS) (Kebede et al., 2025). We finely interpolated grid data to the site-level to compute irrigation share at each location. The average irrigation shares for 2000 to 2015 are shown in **Fig. S5**. Here, the total harvested area of winter wheat was calculated as the sum of the irrigated and rainfed wheat areas. The irrigation share (I) was then the irrigated area divided by the total harvested area at each site. Due to the absence of irrigation data, we assumed no change in irrigation share since 2015.”

Accordingly, we revised Equation 1 to include irrigation share (I) as a covariate. This enables us to examine whether and how irrigation moderates the sensitivity of wheat yields to extreme climate stressors such as EDD and CDD.

The updated equation 1 in our revision is as below:

$$\text{Log Yield}_{d,t} = \sum_{j=2}^3 \beta_{1,j} \text{FDD}_{d,t}^j + \sum_{j=3}^4 \beta_{2,j} \text{EDD}_{d,t}^j + \sum_{j=2}^4 \beta_{3,j} \text{CDD}_{d,t}^j + \beta_4 \text{CHD}_{d,t} + \sum_{j=2}^3 \beta_{5,j} \text{CFD}_{d,t}^j + \beta_6 I_{d,t} + \alpha_d + \beta_{7,d} t + \beta_{8,d} t^2 + \varepsilon_{d,t} \quad (1)$$

Moreover, we added some sentences in Lines 451-455:

“Since wheat statistical yield data in our study region does not provide information on irrigated and rainfed yields separately, we are unable to directly estimate the impact of weather on each type. Therefore, to measure the change in sensitivity of yields to weather, we include the share of wheat-specific irrigated area ($I_{d,t}$), which we use as our measure of wheat irrigation (Zaveri and Lobell, 2019).”

Accordingly, our process-based simulations were designed to incorporate irrigation management. Specifically, we used the automatic irrigation setting within process-based model to approximate actual field practices (Chen et al., 2018). That is, wheat crop yields were simulated based on actual irrigation management practices. We set automatic irrigation as crop water demand required because of spatially heterogeneous nature of irrigation across the region, driven by the dominance of smallholder farming in China (Li and Lei, 2021). From previous studies, irrigation in our study area varies substantially across provinces, within counties, and even among neighboring plots (Zhao et al., 2023). In general, northern North China Plain regions are more reliant on irrigation, while the southern North China Plain tends to be rainfed (Xiao and Tao, 2014; Zhao et al., 2023).

Therefore, we added some sentences in Lines 477-480 for our process-based model simulation:

“Here, irrigation was considered during model simulation. Given the spatially heterogeneous nature of irrigation across the region, the automatic irrigation setting within the model was used to approximate actual field practices. That is, wheat crop yields were simulated based on actual irrigation management practices.”

In addition, we conducted a comparative analysis using models with and without irrigation share as a control variable (see **Figs. R1-R2** below). While the direction of the estimated effects of extreme degree days (EDD) on yield remained consistent, the effect sizes were moderately larger in models that included irrigation, suggesting that excluding irrigation may lead to a lower climate sensitivity. A similar pattern was observed for consecutive dry days (CDD). These findings are consistent with the results by Zaveri and Lobell (2019), who noted that models without irrigation controls tend to yield lower-bound estimates. Therefore, we are confident that our results are robust and reflective of irrigation as a control variable does not alter the key patterns observed.

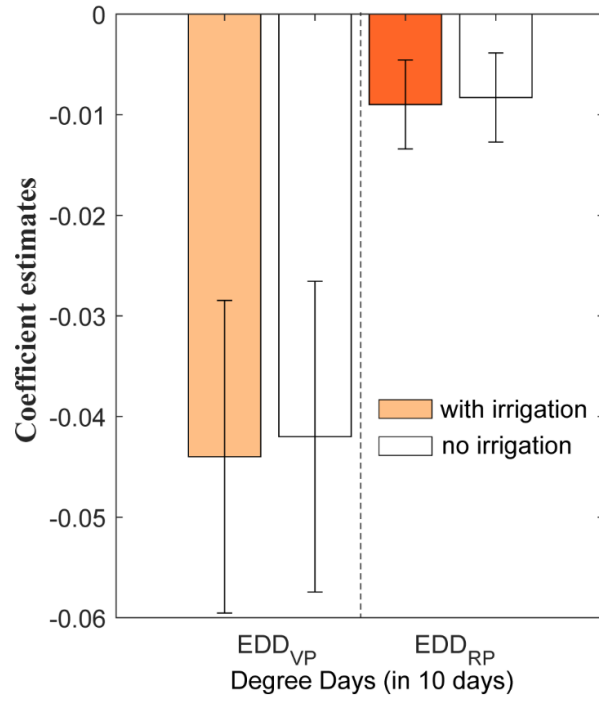


Fig. R1. Impacts of EDD_{VP} and EDD_{RP} on log wheat yield with and without irrigation controls.

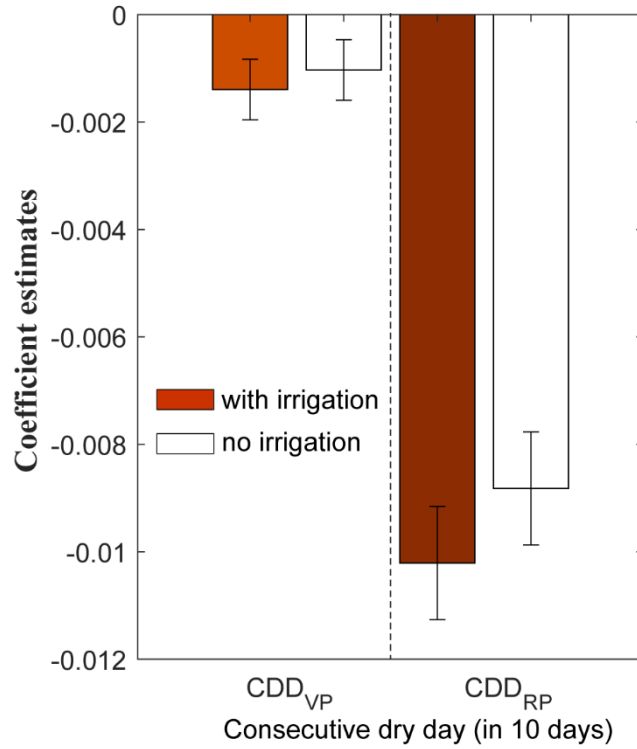


Fig. R2. Impacts of CDD_{VP} and CDD_{RP} on log wheat yield with and without irrigation controls.

Therefore, we added the following sentences to the Discussion section as below:

Lines 329-337: “It should be noted that our analysis explicitly incorporates irrigation, as it might influence local microclimates and regional climate patterns by altering land–atmosphere feedbacks and atmospheric moisture transport (Greve et al., 2025; Li et al., 2023). We included irrigation share as a covariate in our statistical models. We find that the estimated impacts of EDD and CDD on yield generally remain consistent in the same direction (i.e., negative impact) but are slightly larger in magnitude when irrigation is included, suggesting that omitting irrigation may lead to an underestimation of climate sensitivity. This finding is consistent with Zaveri and Lobell (2019), emphasizing that models excluding irrigation effects tend to provide lower-bound estimates of heat sensitivity.”

Additionally, we revised **Figs. 1-3** and **Figs. 6-7** (see below) and their descriptions (lines 137-173 and lines 220-253) based on updated results as we added irrigation practices.

Fig. 1 Characterization of the study region.

(a) Winter wheat planting patterns (green background map) across each sub-region (north (NS); middle (Huang-Huai, HHS); south (middle-lower reaches of Yangzi River, MYS)). Circles are meteorological observations at irrigated (blue) and rainfed (orange) sites, and red stars indicate locations of experimental sites. (b) Average temperature and (c) Average total precipitation during the winter wheat growing season from 1980 to 2019.

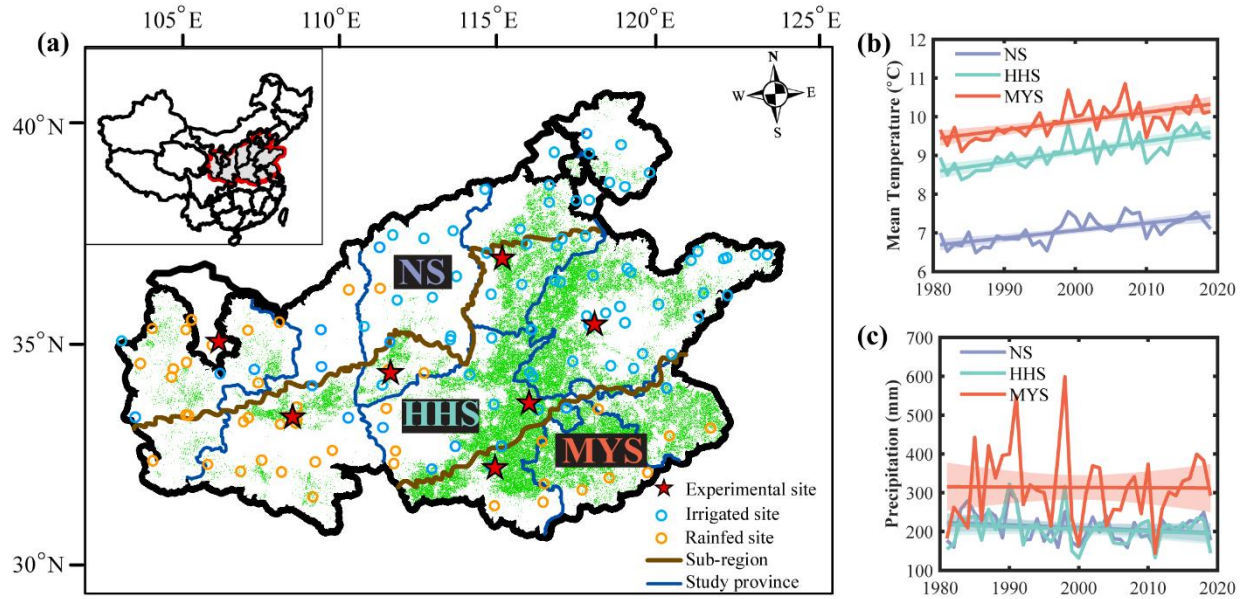


Fig. 2 Impacts of extreme climate indices on wheat yields.

(a) Sensitivity of winter wheat yields to extreme degree days (EDD) and freezing degree days (FDD) in different phenological phases; the error bars refer to 95% confidence intervals. (b) The percent change in yield as a function of the consecutive dry days (CDD) by different growth phases; shaded areas indicate the 95% confidence intervals while histograms show the distribution of CDD occurrence amounts sampled. (c) Changes in sensitivity of wheat yields to all extreme climate indices from 2000 to 2009 (blue shaded) and 2010 to 2019 (pink shaded). The solid circles show estimated mean coefficients from the statistical model; the error bars indicate the 95% confidence intervals.

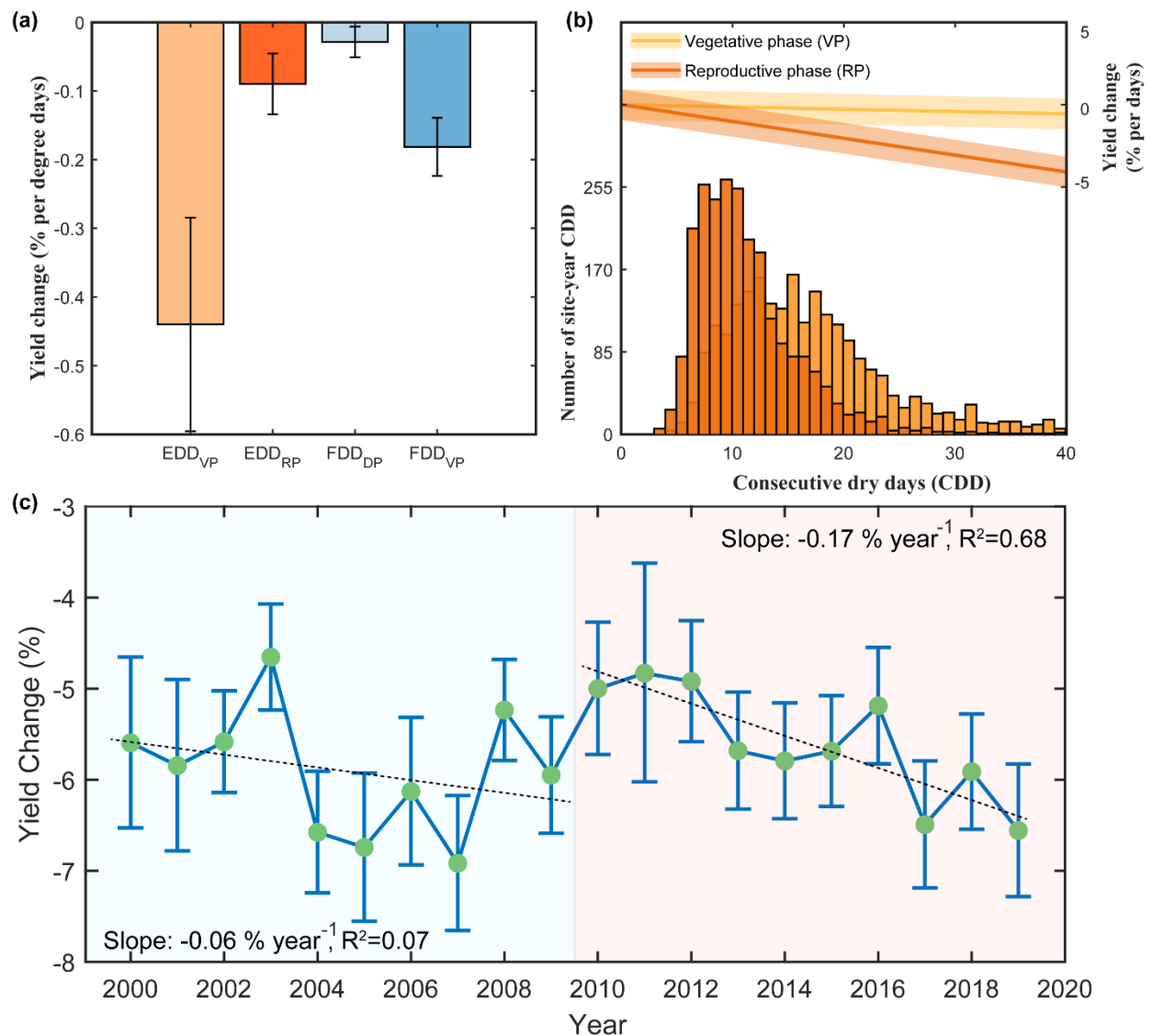


Fig. 3 Impacts of extreme climate indices on wheat yields at three sub-regions.

Yield changes due to extreme climate indices in the (a) north (NS), (b) middle (Huang-Huai, HHS), and (c) south (middle-lower reaches of Yangzi River, MYS) sub-regions. Extreme climate indices are extreme degree days (EDD), freezing degree days (FDD), consecutive dry days (CDD), compound hot-dry days (CHD), and compound freeze-dry days (CFD). The horizontal bars indicate the 95% confidence interval of the average value (solid dots). DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).

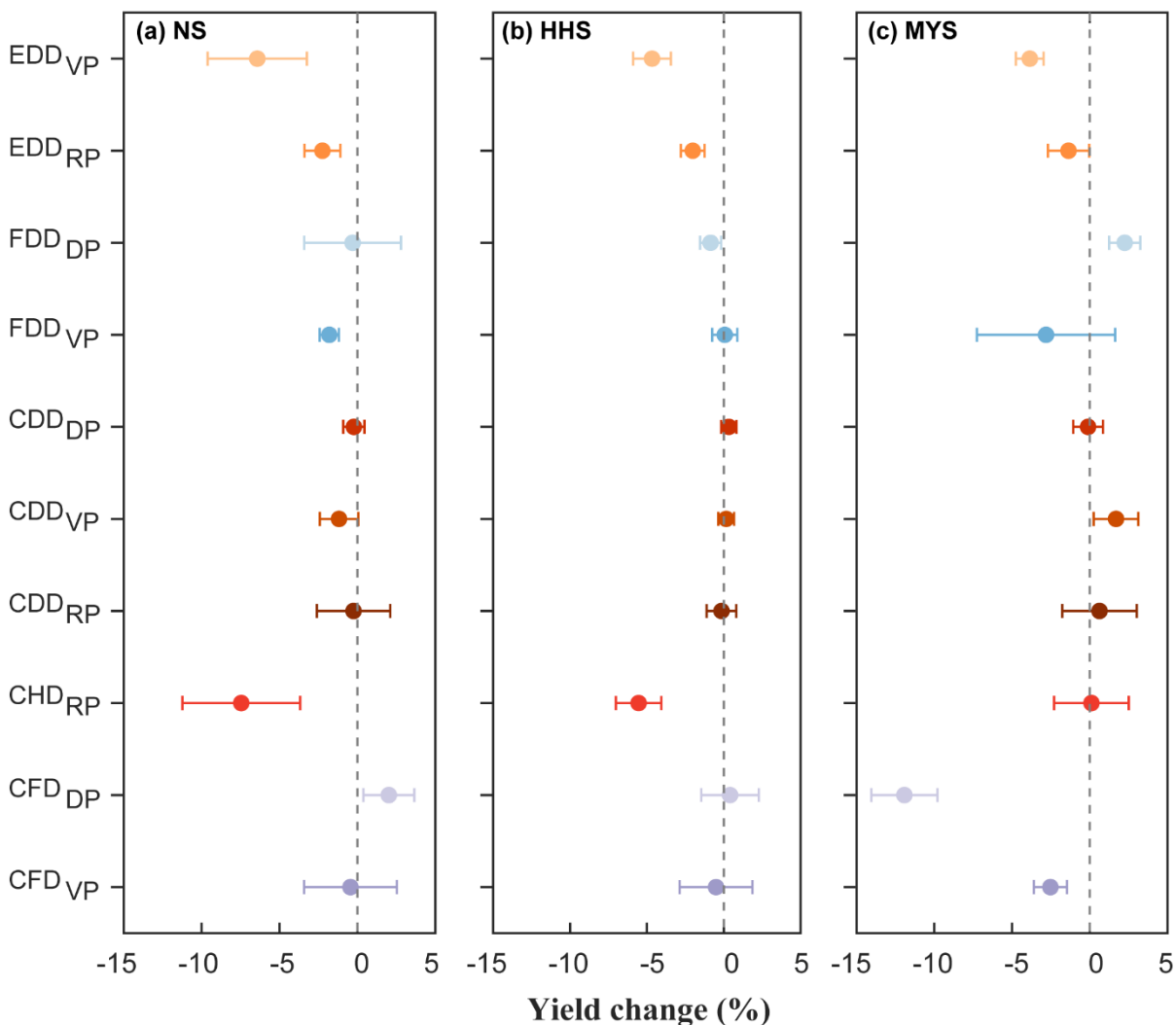


Fig. 6 Comparison of estimated effects of extreme climate indices on wheat yields.

Yield changes based on the process-based crop model and statistical model under (a-b) extreme degree days (EDD), (c-d) freezing degree days (FDD), (e-g) consecutive dry days (CDD), (h) compound hot-dry days (CHD), and (i-j) compound freeze-dry days (CFD). Black lines and blue lines are statistical modeling and process-based modeling, respectively. DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).

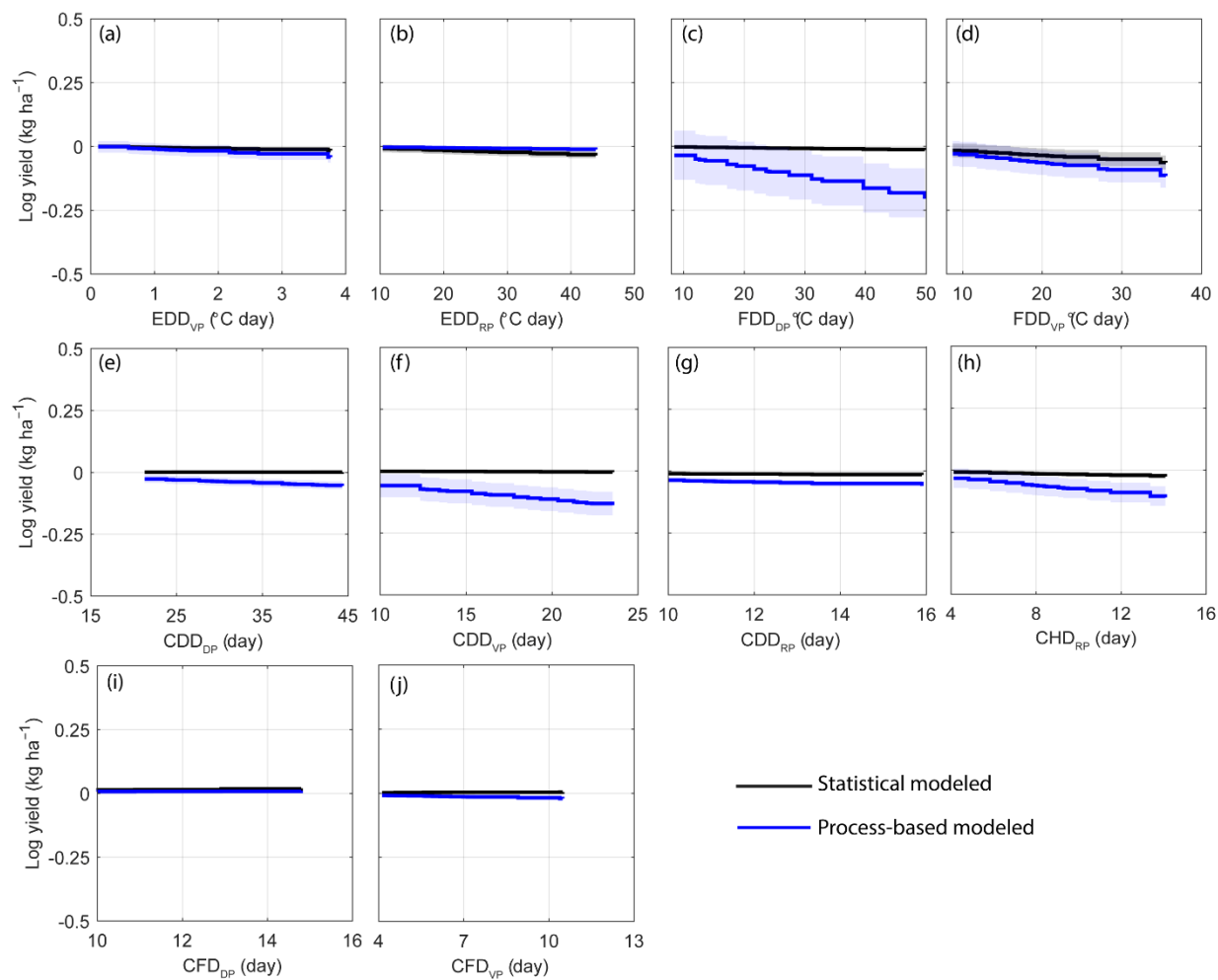
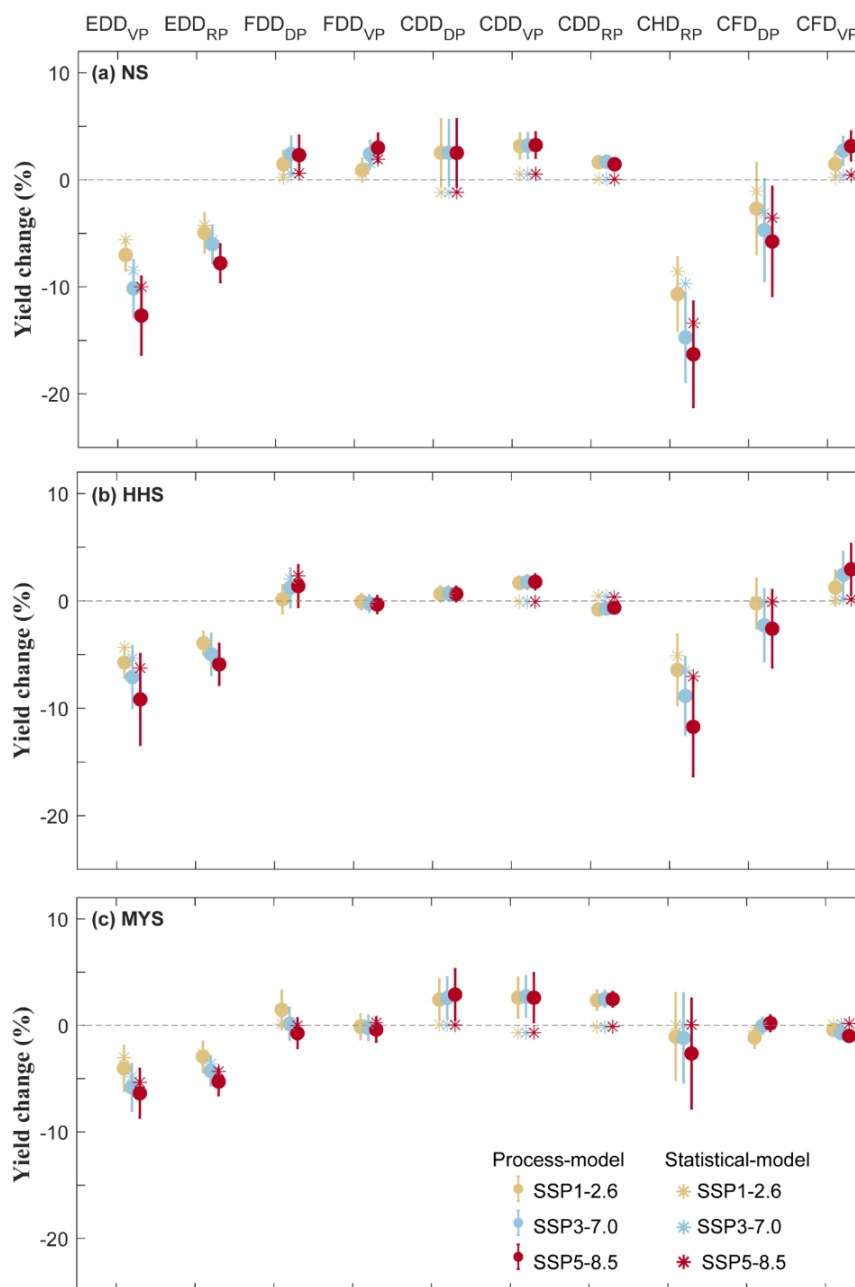


Fig. 7. Impact of extreme climate indices on wheat yields by 2080-2100 under SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios.

Estimated effects of future changes in extreme climate indices on wheat yields, derived from both the process-based and statistical models for the (a) north (NS), (b) middle (Huang-Huai, HHS), and (c) south (middle-lower reaches of Yangzi River, MYS) sub-regions. Extreme climate indices are extreme degree days (EDD), freezing degree days (FDD), consecutive dry days (CDD), compound hot-dry days (CHD), and compound freeze-dry days (CFD). The vertical bars indicate the 95% confidence interval of the average value (solid dots). DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity).



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End of Response to Reviewer 2.

Reviewer #3 (Remarks to the Author) for COMMSENV-25-0409A:

I think the authors have revised the manuscript well. Thanks for letting me review the paper.

Response: Thank you for your recognition and valuable feedback on our manuscript.

End of Response to Reviewer 3.

Point-by-point Responses to Reviewer 1 for COMMSENV-25-0409B

We greatly appreciate these insightful comments and suggestions to improve our manuscript. Reviewers 2 and 3 had no further comments, and we greatly appreciate their positive remarks. The following pages contain our point-by-point response to Reviewer 1. The comments are shown in regular fonts, our responses are in blue fonts.

Reviewer #1 (Remarks to the Author) for COMMSENV-25-0409B:

*The figure 7 has been included for yield changes from statistical and process-based models, but this result is inconsistent with figure 6. Figure 6 shows more yield reduction for most of extreme climate indices in the process-based model than the statistical model, for example, FDD_DP, CDD_VP, CDD_DP, and CHD_RP. However, Figure 7 shows CDD_VP's yield is lower in the statistical model than in the process-based model, which I do not expect. CHD_RP in Figure 7 is consistent with Figure 6; yield is lower for the process-based model than the statistical model.

Response: We appreciate your insights. The apparent discrepancy arises because Figures 6 and 7 present different quantities at different spatial scales. Specifically, Figure 6 shows historical marginal sensitivities (β) for the entire study area, while Figure 7 reports projected yield changes ($\beta \cdot \Delta X$) for three subregions (NS, HHS, MYS), where ΔX denotes the projected changes in EDD, FDD, CDD, CHD, and CFD under future scenarios. Therefore, the visual patterns in Figure 6 cannot be directly compared with the projections in Figure 7.

For CDD indices, the estimated coefficients are negative in both models ($\beta < 0$, more dry days reduce yield). Projections, however, indicate $\Delta CDD < 0$ (fewer dry days in the future). Thus, $\beta \cdot \Delta CDD$ becomes positive, implying a yield benefit. Because the process-based model has a more negative coefficient (i.e., $|\beta_{\text{process}}| > |\beta_{\text{stat}}|$), it produces a larger positive contribution than that from statistical model in Figure 7. This explains why CDD_VP appears “lower” in the statistical model, which reflects a smaller positive bar rather than a contradiction.

For indices with $\Delta X > 0$ (e.g., CHD_RP), a more negative coefficient in the process-based model leads to a more negative $\beta \cdot \Delta X$, which is consistent between Figures 6 and 7.

In summary, Figures 6 and 7 are complementary rather than inconsistent. Figure 6 reflects historical sensitivities, while Figure 7 combines these sensitivities with region-specific projected changes in climate indices. We hope this distinction clarifies the results, and we are confident that our findings provide a consistent and robust assessment of how extreme climate events will shape future wheat yield.

End of Response for Reviewer 1.

Reviewer #2 (Remarks to the Author) for COMMSENV-25-0409B:

I have no further comments at this time.

However, given the valuable field data available, I was particularly interested in exploring the different responses of rainfed versus irrigated wheat to climate extremes. Maybe this is not the major focus of the study.

Response: We appreciate your encouraging review. Your comments and suggestions substantially improved the quality of this study.

Yes, we agree that comparing responses of extreme climate events between rainfed to irrigated wheat warrants a valuable study in future, and while not the focus in this current study, we look forward to investigating this in future study.

End of Response to Reviewer 2.

Reviewer #3 (Remarks to the Author) for COMMSENV-25-0409B:

I am good with revision. Thanks.

Response: Thank you for your valuable feedback on our manuscript.

End of Response to Reviewer 3.