

Supplementary Information for

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

Ruiyun Zeng^{1, 2, 3}, Xiaomao Lin^{1, *}, Gretchen F. Sassenrath¹, Stephen M. Welch¹,
Fengmei Yao^{3, *}

¹ Department of Agronomy, Kansas State University, 2004 Throckmorton Hall, Plant Sciences Center, Manhattan, Kansas, USA

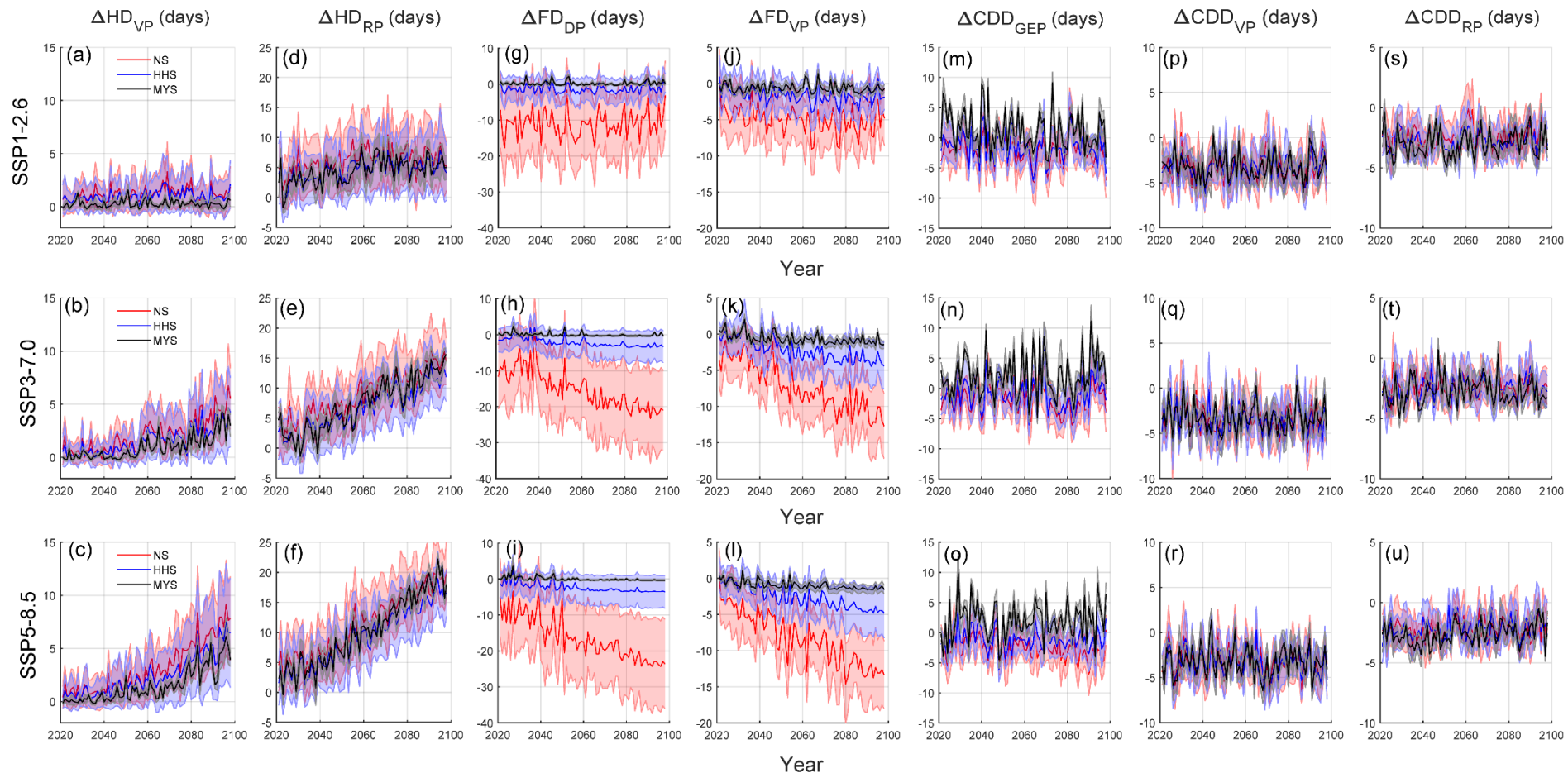
² Center for Geospatial Analytics, North Carolina State University, Raleigh, North Carolina, USA

³ College of Earth and Planetary Sciences, University of Chinese Academy of Sciences, Beijing, People's Republic of China

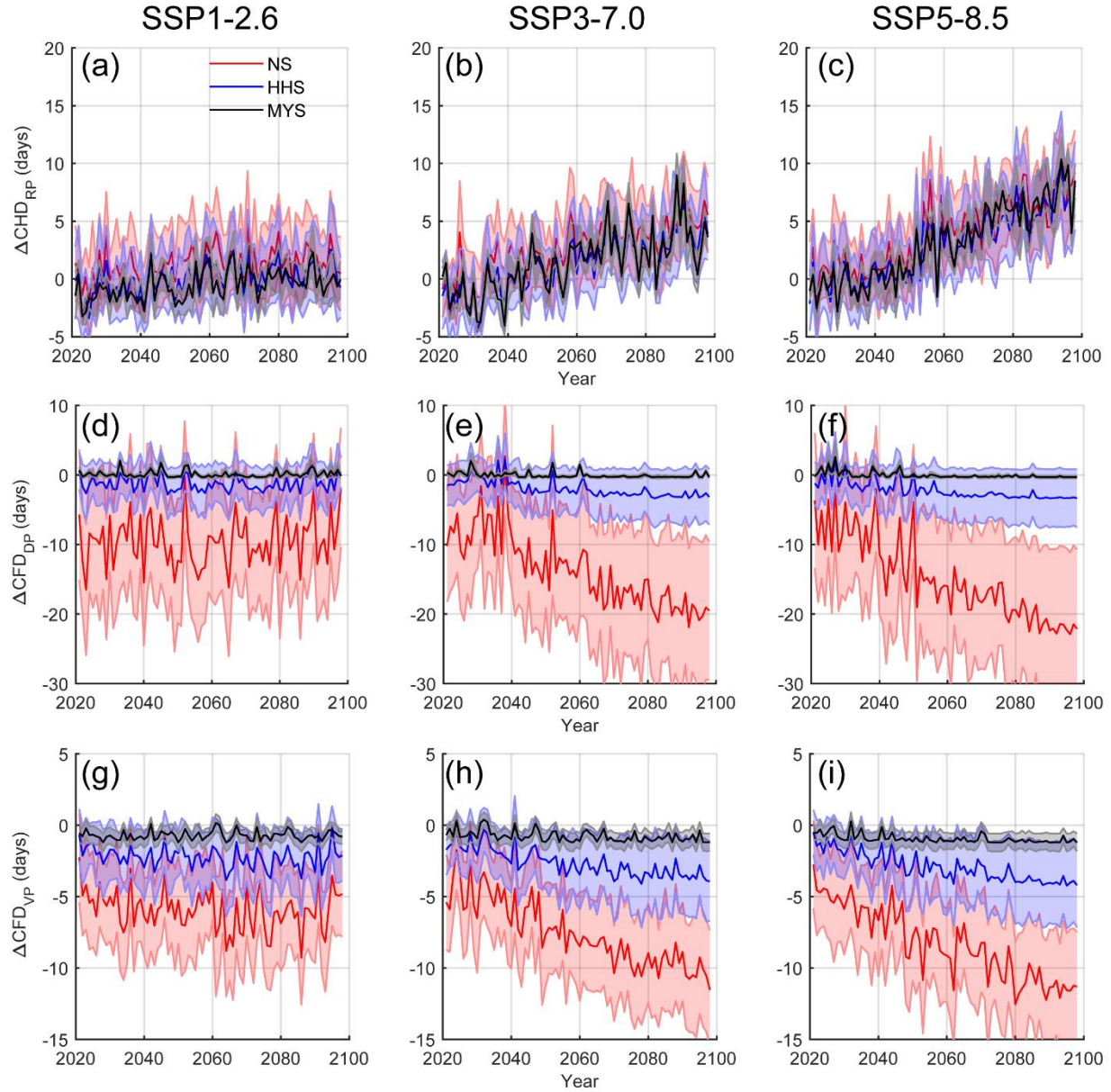
*** Corresponding author:**

Dr. Xiaomao Lin, xlin@ksu.edu

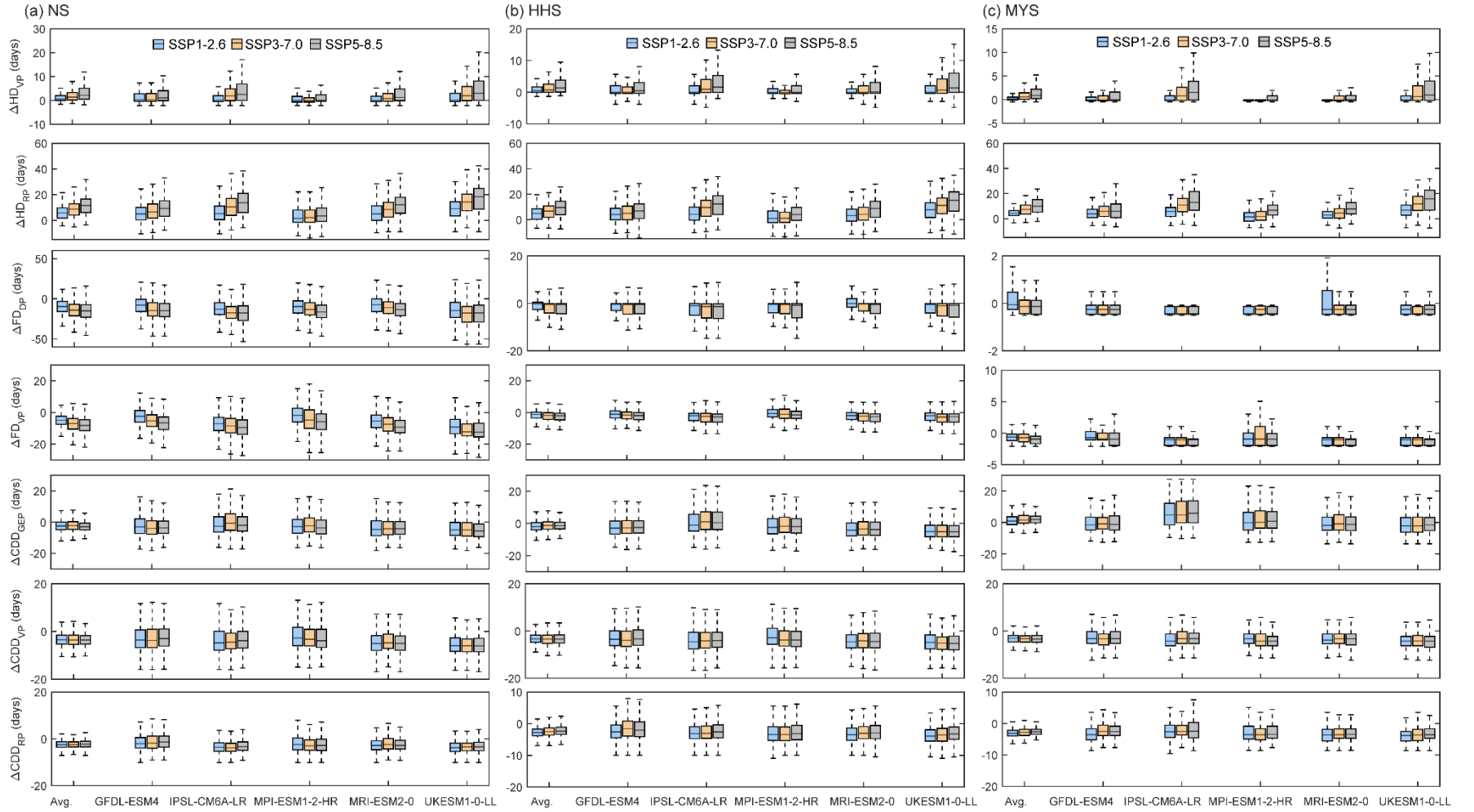
Dr. Fengmei Yao, yaofm@ucas.ac.cn



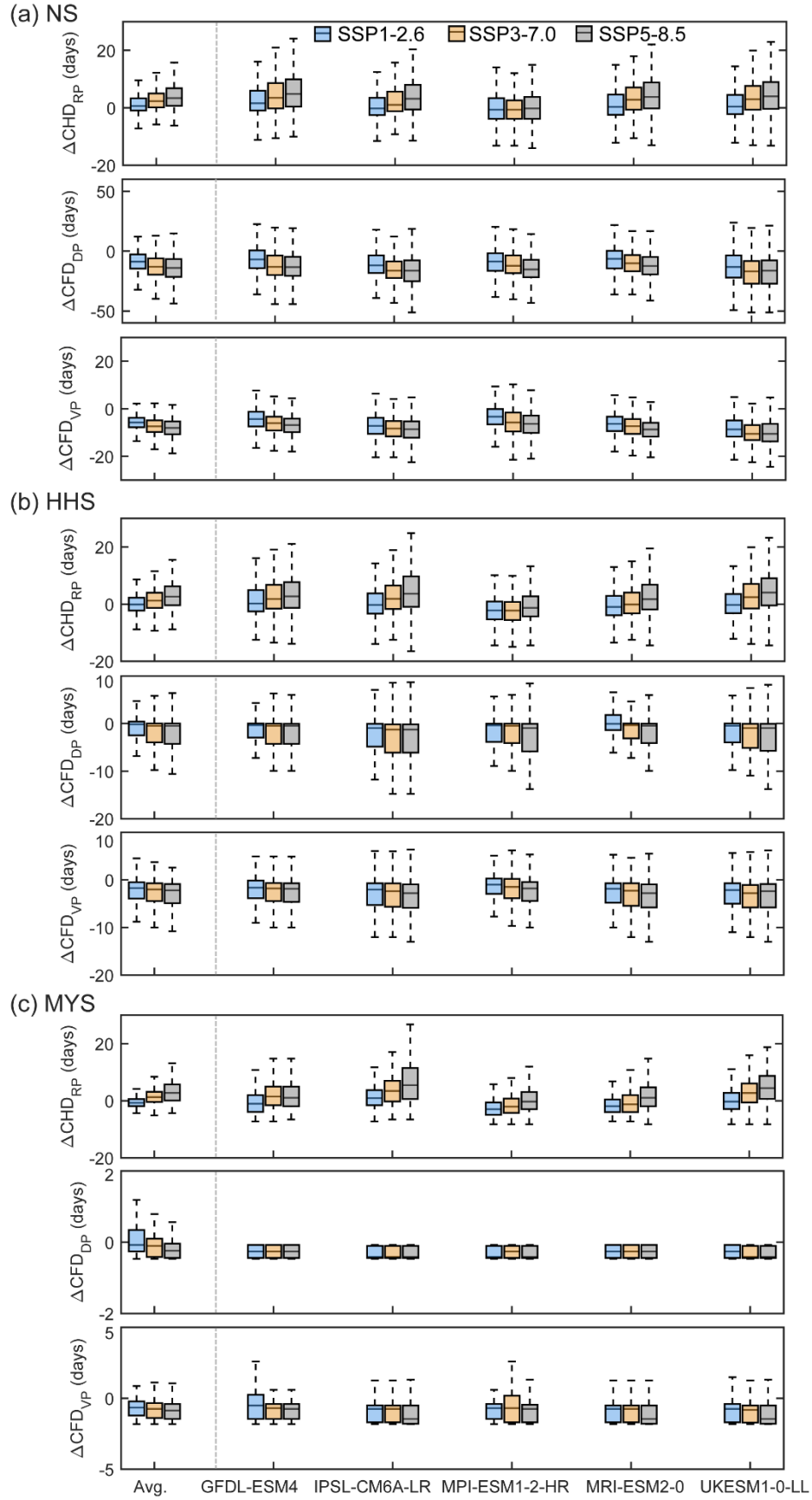
Supplementary Figure 1. Time series of projected changes (Δ) in hot days (HD) (a-f), freeze days (FD) (g-l), and consecutive dry days (CDD) (m-u) during growth phases under SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. Future climate projections are based on the ensemble of climate model outputs. GEP is 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). Solid lines indicate the mean values, and the shaded areas represent ± 1 standard deviation.



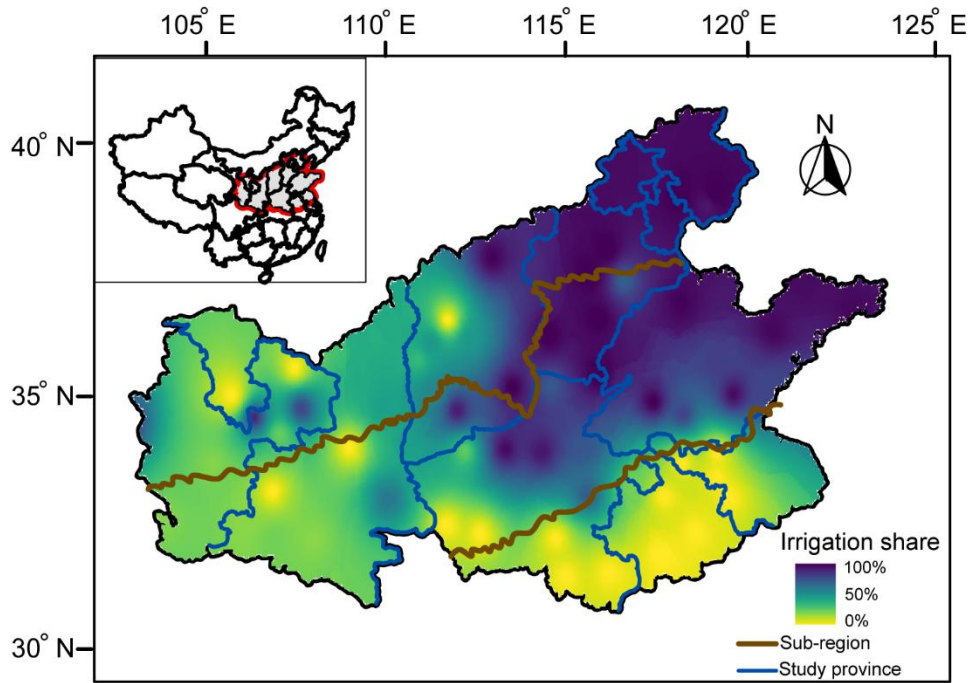
Supplementary Figure 2. Time series of projected changes (Δ) in compound hot-dry days (CHD) (a-c) and compound freeze-dry days (CFD) (d-i) during growth phases under SSP1-2.6, SSP3-7.0, and SSP5-8.5 scenarios. Future climate projections are based on the ensemble of climate model outputs. DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity). Solid lines indicate the mean values, and the shaded areas represent ± 1 standard deviation.



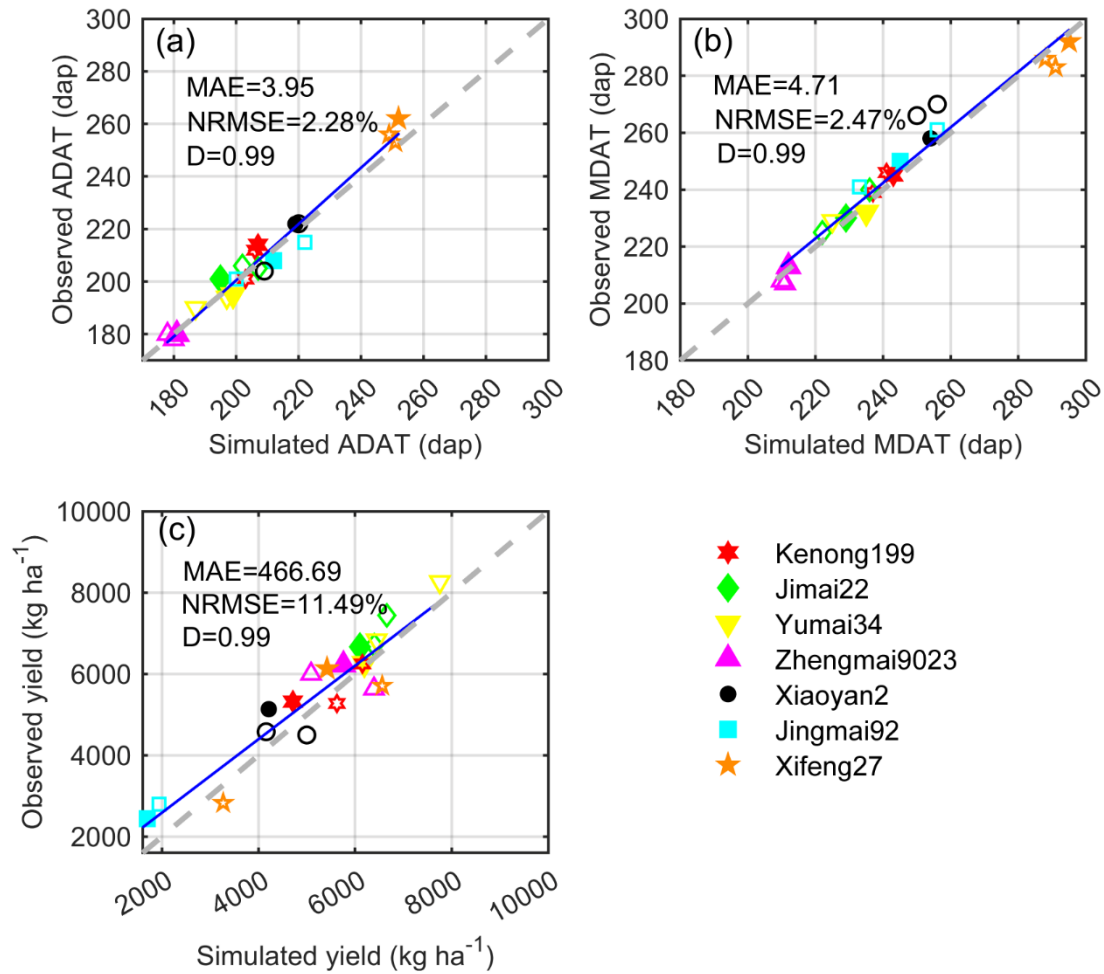
Supplementary Figure 3. Boxplot of projected changes for (Δ) hot days (HD), freeze days (FD), and consecutive dry days (CDD) during growth phases under three future climate scenarios for NS (a), HHS (b), and MYS (c) sub-regions. GEP is the germination and establishment phase (planting to November); DP is the dormancy phase (December to February); VP is the vegetative phase (March to Anthesis); RP is the reproductive phase (Anthesis to Maturity). Boxplots indicate the median (horizontal black line), 25-75th percentile (box), and 5-95th percentile (whiskers) of estimated changes in all year and location combinations for three sub-regions.



Supplementary Figure 4. 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 for NS (a), HHS (b), and MYS (c) 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). Boxplots indicate the median (horizontal black line), 25-75th percentile (box), and 5-95th percentile (whiskers) of estimated changes in all year and location combinations for three sub-regions.



Supplementary Figure 5. 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.



Supplementary Figure 6. 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.

Supplementary Table 1. Impact of extreme climate indices on wheat yield.

Climate indices	NS	HHS	MYS
EDD _{VP}	-0.064 (0.003)	-0.047 (0.001)	-0.038 (0.001)
EDD _{RP}	-0.023 (0.001)	-0.020 (0.001)	-0.014 (0.001)
FDD _{DP}	-0.003 (0.003)	-0.008 (0.001)	0.022 (0.001)
FDD _{VP}	-0.018 (0.001)	0.001 (0.001)	-0.028 (0.004)
CDD _{DP}	-0.002 (0.001)	0.003 (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)	-0.055 (0.001)	0.001 (0.002)
CFD _{DP}	0.020 (0.002)	0.004 (0.002)	-0.120 (0.002)
CFD _{VP}	-0.004 (0.003)	-0.005 (0.002)	-0.025 (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.

Supplementary Table 2. The freezing growing temperature threshold (T_{frez}, °C) in each phenological phase for winter wheat in our study and other research.

Jiang et al., 2025 ¹ , Porter and Gawith, 1999 ²			Our study	
Month	Growing stages	T _{frez} (°C)	Categorized stage	T _{frez} (°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		

Supplementary Table 3. Co-linearity analysis of climate variables.

Variables	VIF
HD	9.612
EDD	4.4598
CHD	8.7558

Supplementary Table 4. Derived genetic parameters of seven cultivars in 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 ($^{\circ}\text{C}\cdot\text{d}$)

Supplementary Table 5. 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</i> <i>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 ³
			282	2013	6670	Bian et al., 2016 ⁴
			280	2014	6710	
Shangqiu (34°27'N, 115°40'E)	<i>Yumai34</i>	Clay loam	285	2012	6255	Shangqiu Agro-ecosystem Experimental Station
			284	2013	6831	
			284	2014	8264	
Zhumadian (33°00'N 114°02'E)	<i>Zhengmai</i> <i>9023</i>	Loam	296	2006	5625	Zhumadian Agro-meteorological station and Xiao and Tao, 2014 ⁵
			299	2007	6225	
			302	2008	6000	
Yangling (34°17'N, 108°04'E)	<i>Xiaoyan2</i>	Loess	263	2007	5135	Zhang et al., 2018 ⁶
			268	2009	4500	
			268	2013	4579	
Wenxi (35°20'N, 111°17'E)	<i>Jingmai</i> <i>92</i>	Loess	271	2009	2800	Xue et al., 2019 ⁷
			280	2010	2440	Sun et al., 2018 ⁸
			276	2013	1880	
Guyuan (35°79'N, 106°45'E)	<i>Xifeng 27</i>	Loess	263	2009	2829	Ren et al., 2016 ⁹
			260	2013	5702	Wei et al., 2018 ¹⁰
			264	2014	6135	

Supplementary References:

1. Jiang T, He L, Feng H, He J, Yu Q. Understanding the impacts of extreme temperature and humidity compounds on winter wheat traits in China. *Agric For Meteorol* **362**, 110354 (2025).
2. Porter JR, Gawith M. Temperatures and the growth and development of wheat: a review. *Eur J Agron* **10**, 23-36 (1999).
3. Qi L, Chen YH, Zhou XB, Liu Y, Gao HJ. Effects of planting patterns on water use efficiency in winter wheat. *Acta Ecologica Sinica* **7**, 1888-1895 in Chinese with English abstract (2011).
4. Bian C, *et al.* Responses of Winter Wheat Yield and Water Use Efficiency to Irrigation Frequency and Planting Pattern. *PLoS ONE* **11**, e0154673 (2016).
5. Xiao D, Tao F. 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 (2014).
6. Zhang Y, *et al.* The effects of rotating conservation tillage with conventional tillage on soil properties and grain yields in winter wheat-spring maize rotations. *Agric For Meteorol* **263**, 107-117 (2018).
7. Xue LZ, *et al.* Effects of tillage practices on water consumption and grain yield of dryland winter wheat under different precipitation distribution in the loess plateau of China. *Soil and Tillage Research* **191**, 66-74 (2019).
8. Sun M, *et al.* Long-term evaluation of tillage methods in fallow season for soil water storage, wheat yield and water use efficiency in semiarid southeast of the Loess Plateau. *Field Crops Res* **218**, 24-32 (2018).
9. Ren X, Cai T, Chen X, Zhang P, Jia Z. Effect of rainfall concentration with different ridge widths on winter wheat production under semiarid climate. *Eur J Agron* **77**, 20-27 (2016).
10. Wei T, *et al.* Effects of rainwater harvesting planting combined with deficiency irrigation on soil water use efficiency and winter wheat (*Triticum aestivum* L.) yield in a semiarid area. *Field Crops Res* **218**, 231-242 (2018).