Supplement of

Improving wheat phenology and yield forecasting with a deep learning-enhanced WOFOST model under extreme weather conditions

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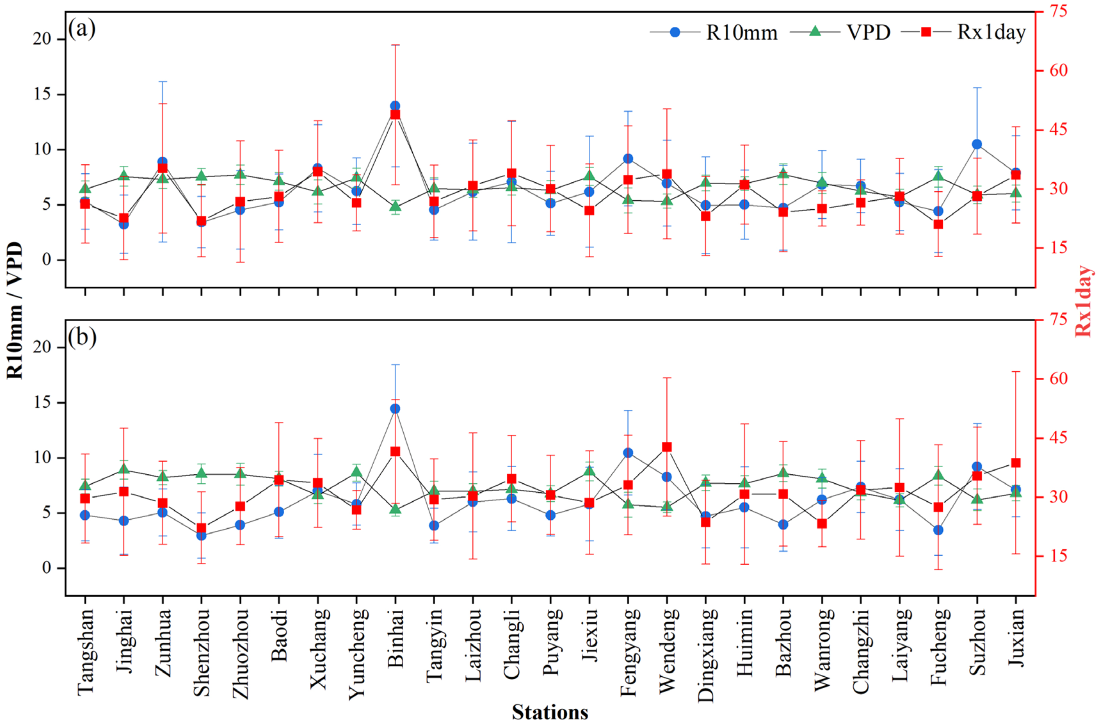

Figure S1. The extreme weather index results for the 25 counties in the study area for the calibration years (a) and validation years (b). R10mm and Rx1day represent extreme precipitation-related weather indices. VPD represents vapor pressure deficit.

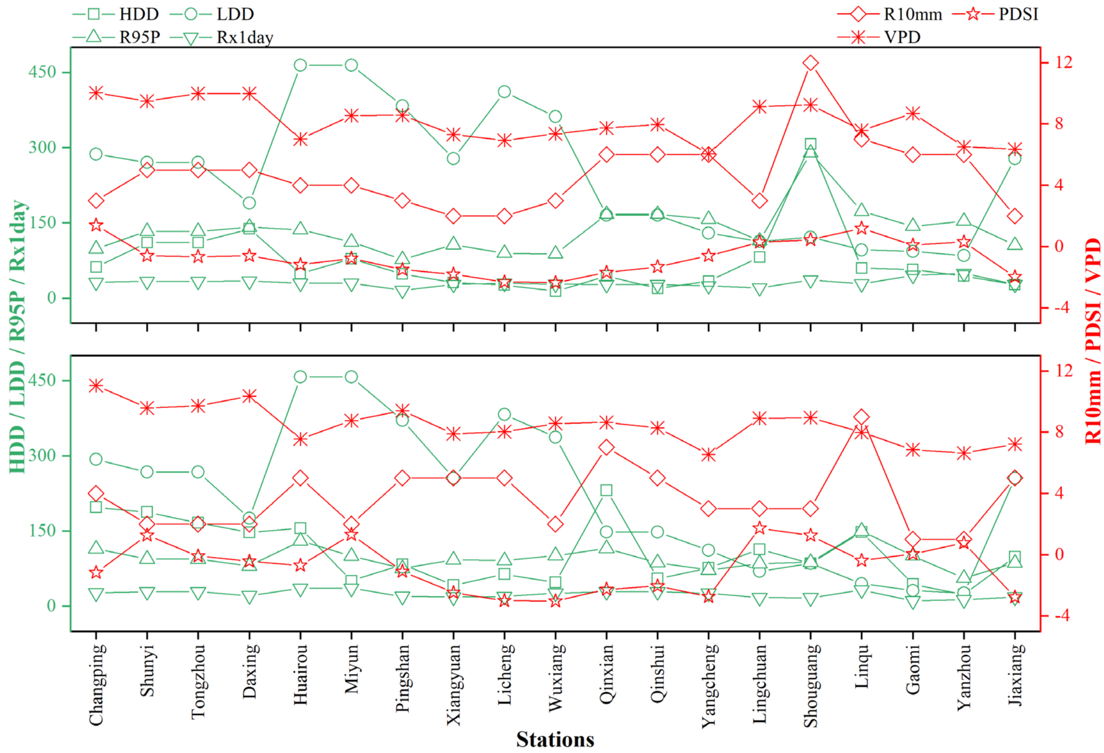

Figure S2. Results of extreme weather indices at counties affected by extreme weather in 2008 (a) and 2018 (b). HDD and LDD represent weather indices related to extreme temperatures; R95P, R10mm, and Rx1day represent weather indices related to extreme precipitation. PDSI stands for the Palmer Drought Severity Index, and VPD represents Vapor Pressure Deficit.

Table S1. Detailed information in the study counties affected by extreme weather in 2008 and 2018.

Counties	Longitude	Latitude	Affected year	Extreme weather type
Changping	116.2 °E	40.2 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Shunyi	116.7 °E	40.2 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Tongzhou	116.7 °E	39.8 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Daxing	116.4 °E	39.6 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Huairou	116.6 °E	40.6 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Miyun	117.0 °E	40.5 °N	2008	Heavy rain, Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Pingshan	113.9 °E	38.4 °N	2008	High-temperature drought
			2018	Heavy rain
Xiangyuan	113.0 °E	36.6 °N	2008	High-temperature drought
			2018	Low-temperature freeze damage
Licheng	113.4 °E	36.6 °N	2008	High-temperature drought
			2018	Heavy rain
Wuxiang	113.0 °E	36.9 °N	2008	High-temperature drought
			2018	Heavy rain
Qinxian	112.6 °E	36.7 °N	2008	High-temperature drought
			2018	Low-temperature freeze damage
Qinshui	112.4 °E	35.7 °N	2008	High-temperature drought
			2018	Low-temperature freeze damage
Yangcheng	112.4 °E	35.4 °N	2008	High-temperature drought
			2018	Low-temperature freeze damage
Lingchuan	113.3 °E	35.7 °N	2008	High-temperature drought
			2018	High-temperature drought
Shouguang	118.8 °E	37.0 °N	2008	Low-temperature freeze damage
			2018	Heavy rain
Linqu	118.6 °E	36.4 °N	2008	Heavy rain
			2018	Heavy rain
Gaomi	119.7 °E	36.4 °N	2008	Low-temperature freeze damage
			2018	Heavy rain, Low-temperature freeze damage
Yanzhou	116.7 °E	35.6 °N	2008	Heavy rain
			2018	Heavy rain, Low-temperature freeze damage
Jiaxiang	116.3 °E	35.4 °N	2008	Heavy rain
			2018	Heavy rain, Low-temperature freeze damage

Table S2. Detailed descriptions and initial ranges of crop parameters in the WOFOST model. WWH107.CAB is a default parameter file available on the official website (https://www.wur.nl).

Parameter	Description	Unit	Range or source
TBASEM	Lower threshold temperature for emergence	℃	0.0
TEFFMX	Maximum effective temperature for emergence	℃	30.0
TSUMEM	Temperature sum from sowing to emergence	℃ d	105.0
IDSL	Development rate determinants before the flowering stage	-	0.0
DLO	Optimal photoperiod for development	hr	14.5
DLC	Critical day length for development (lower threshold)	hr	8.0
TSUM1	Accumulated temperature from emergence to flowering	℃ d	1300-1600
TSUM2	Accumulated temperature from flowering to maturity	℃ d	650.0
DTSMTB	Daily increase in temperature sum as a function of daily mean temperature	℃	WWH107.CAB
DVSI	Development stage at emergence	-	0.0
DVSEND	Development stage at maturity	-	2.0
TDWI	Initial total dry weight	$kg\cdot ha^{-1}$	WWH107.CAB
LAIEM	Leaf area index at emergence	$kg\cdot ha^{-1}\cdot d^{-1}$	0.0007-0.30
RGRLAI	Maximum relative increase in leaf area index	$ha\cdot ha^{-1}\cdot d^{-1}$	0.00817
SLATB	Specific leaf area at corresponding development stage	$ha\cdot kg^{-1}$	0.001-0.004
SPA	Specific pod area	$ha\cdot kg^{-1}$	0.0
SSA	Specific stem area	$ha\cdot kg^{-1}$	0.0
SPAN	Leaf senescence coefficient	d	20.0-50.0
TBASE	Lower temperature limit for leaf age	℃	-10.0-10.0
KDIF	Extinction coefficient for diffuse visible light as a function of development stage	-	0.6
EFFTB	Initial light uses efficiency of CO_2 assimilation of single leaves as a function of daily mean temperature	$kg\cdot hm^{-2}\cdot hr^{-1}\cdot j^{-1}\cdot m^2\cdot s$	0.1-0.4
AMAX	Maximum CO_2 assimilation rate at corresponding development stage	$kg\cdot hm^{-2}\cdot hr^{-1}$	WWH107.CAB
TMPF	Daytime average temperature effect on maximum CO_2 assimilation rate	-	WWH107.CAB
TMNF	Nighttime temperature effect on total assimilation rate	-	WWH107.CAB
CVL	Efficiency conversion of assimilates into leaf dry matter	$kg\cdot kg^{-1}$	0.74
CVO	Efficiency conversion of assimilates into storage organ dry matter	$kg\cdot kg^{-1}$	0.5-0.8
CVR	Efficiency conversion of assimilates into root dry matter	$kg\cdot kg^{-1}$	0.69
CVS	Efficiency conversion of assimilates into stem dry matter	$kg\cdot kg^{-1}$	0.74
Q10	Increase of the respiration rate per 10 °C temperature increase	-	2.0
RML	Relative maintenance respiration rate for leaves	$kg\cdot CH_2O\cdot kg^{-1}\cdot d^{-1}$	0.03
RMO	Relative maintenance respiration rate for storage organs	$kg\cdot CH_2O\cdot kg^{-1}\cdot d^{-1}$	WWH107.CAB
RMR	Relative maintenance respiration rate for roots	$kg\cdot CH_2O\cdot kg^{-1}\cdot d^{-1}$	0.015
RMS	Relative maintenance respiration rate for stems	$kg\cdot CH_2O\cdot kg^{-1}\cdot d^{-1}$	0.0
RFSE	Relative decrease factor for mortality at corresponding development stage	-	1.0

FR	Allocation coefficient from total dry weight to roots	$kg \cdot kg^{-1}$	WWH107.CAB
RL	Allocation coefficient from aboveground dry weight to leaves	$kg \cdot kg^{-1}$	WWH107.CAB
FS	Allocation coefficient from aboveground dry weight to stems	$kg \cdot kg^{-1}$	WWH107.CAB
FO	Allocation coefficient from aboveground dry weight to storage organs	$kg \cdot kg^{-1}$	WWH107.CAB

Table S3. Root mean square error (RMSE) between the phenological period and yield simulation results for the WOFOST and WOFOST-EW model on the calibration dataset in each counties.

Counties	Phenology (day)				Yield (kg/ha)	
	WOFOST		WOFOST-EW		WOFOST	WOFOST-EW
	Heading	Maturity	Heading	Maturity		
Tangshan	3.7	5.4	2.5	5.4	773.37	589.14
Jinghai	3.8	3.8	2.6	1.0	739.41	474.61
Zunhua	3.7	3.1	4.0	1.5	784.63	485.39
Shenzhou	5.5	7.2	5.0	4.2	529.98	571.58
Zhuozhou	6.4	8.9	5.1	7.0	594.66	396.24
Baodi	5.3	7.0	4.9	4.4	680.63	654.73
Xuchang	4.7	8.2	4.6	6.9	802.56	386.05
Yuncheng	3.8	10.1	3.8	6.8	804.86	714.46
Binhai	10.3	9.7	5.5	2.1	614.97	688.87
Tangyin	9.6	13.1	5.6	8.4	640.65	394.63
Laizhou	7.6	6.7	4.6	5.5	740.81	620.27
Changli	2.2	6.9	3.9	5.9	844.58	563.38
Puyang	5.8	5.4	6.0	2.2	619.23	472.76
Jiexiu	1.4	6.5	0.7	6.1	717.55	526.53
Fengyang	12.8	9.4	4.5	6.4	657.47	627.60
Wendeng	10.2	10.2	5.0	7.4	700.84	295.63
Dingxiang	8.5	10.9	5.7	6.2	355.83	488.31
Huimin	3.8	4.6	3.1	2.9	481.25	519.26
Bazhou	4.5	7.1	4.8	7.5	665.49	468.48
Wanrong	2.5	12.4	2.8	8.7	521.87	598.07
Changzhi	5.0	10.3	4.2	8.7	779.40	557.60
Laiyang	3.6	11.6	4.2	4.7	792.39	596.14
Fucheng	4.3	8.8	2.5	5.9	699.14	611.51
Suzhou	6.8	4.6	5.4	3.5	519.59	488.10
Juxian	7.5	7.0	4.7	5.1	764.12	758.14

Table S4. Root mean square error (RMSE) between the phenological period and yield simulation results for the WOFOST and WOFOST-EW model on the validation dataset in each counties.

Counties	Phenology (day)				Yield (kg/ha)	
	WOFOST		WOFOST-EW		WOFOST	WOFOST-EW
	Heading	Maturity	Heading	Maturity		
Tangshan	4.2	6.9	5.0	6.8	938.19	960.75
Jinghai	3.8	6.0	5.5	7.0	790.60	605.14
Zunhua	4.4	6.2	5.6	7.3	547.16	657.43
Shenzhou	3.5	7.4	6.0	8.8	714.13	418.84
Zhuozhou	3.0	4.5	5.1	7.3	699.40	641.68
Baodi	4.3	4.8	4.8	6.8	918.80	651.05
Xuchang	4.1	3.2	4.7	3.6	824.02	639.53
Yuncheng	4.3	7.3	2.4	4.3	511.74	500.31
Binhai	6.5	7.4	3.3	4.2	761.25	663.29
Tangyin	7.9	10.0	4.6	5.8	616.91	378.98
Laizhou	4.8	9.3	3.9	6.4	552.23	683.83
Changli	9.5	6.0	4.7	3.9	301.43	565.89
Puyang	5.5	5.3	4.5	4.5	632.95	529.37
Jiexiu	5.7	10.8	4.7	8.2	616.06	515.65
Fengyang	3.1	5.5	4.4	5.9	906.73	586.79
Wendeng	2.0	5.3	4.0	6.8	648.87	386.52
Dingxiang	6.7	11.8	3.7	5.7	794.52	893.47
Huimin	1.7	7.7	4.3	6.9	559.67	536.54
Bazhou	4.0	5.5	1.0	6.8	862.60	383.14
Wanrong	1.0	10.6	1.1	8.1	619.98	703.24
Changzhi	4.6	5.4	4.7	5.2	573.08	297.47
Laiyang	8.5	6.2	4.3	3.2	256.61	279.64
Fucheng	5.4	5.9	4.2	6.9	769.21	453.30
Suzhou	4.4	4.8	4.4	4.6	342.92	390.50
Juxian	4.4	11.1	3.0	7.3	436.12	531.86