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EURAGR-25116; No. of Pages 12

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Europ. J. Agronomy xxx (2012) xxx–xxx

Contents lists available at SciVerse ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

Modeling the response of rice phenology to climate change and variability in different climatic zones: Comparisons of five models

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ARTICLE INFO

Article history:
Received 17 September 2012
Accepted 17 October 2012

Keywords:
Climate change
Extreme temperature
Maturity date
Phenology change
Rice phenology model

ABSTRACT

Crop models have been widely used in simulating and predicting changes in rice phenology in the major rice production regions of China, however the uncertainties in simulating crop phenology at a large scale and from different models were rarely investigated. In the present study, five rice phenological models/modules (i.e., CERES-Rice, ORYZA2000, RCM, Beta Model, SIMRIW) were firstly calibrated and validated based on a large number of rice phenological observations across China during 1981–2009. The inner workings of the models, as well as the simulated phenological response to climate change/variability, were compared to determine if the models adequately handled climatic changes and climatic variability. Results showed these models simulated rice phenological development over a large area fairly well after calibration, although the relative performance of the models varied in different regions. The simulated changes in rice phenology were generally consistent when temperatures were below the optimum; however varied largely when temperatures were above the optimum. The simulated rice growing season under future climate scenarios was shortened by about 0.45–5.78 days; but in northeastern China, increased temperature variability may prolong the growing season of rice. We concluded more modeling and experimental studies should be conducted to accelerate understanding of rice phenology development under extreme temperatures.

1. Introduction

Plant phenology is sensitive to climate change, so phenological changes are often used to measure how climate change affects ecosystems (Myneni et al., 1997; White et al., 1997; Bradley et al., 1999; Abu-Asab et al., 2001; Zhang et al., 2004; Tao et al., 2008a; White et al., 2009). Many researchers have used phenological data to study changes of plant phenology and how plants respond to climate change (Sacks and Kucharik, 2011; Shimono, 2011; Vitasse et al., 2011; Siebert and Ewert, 2012; Tao et al., 2012). Phenological sub-models have been widely used in ecosystem productivity models, land surface process models and crop simulation models (White et al., 1997; Chuine, 2000; Martin et al., 2010; Andrej et al., 2011). The use of robust phenological models has become a crucial simulation tool used to improve the predictive accuracy of recently developed models that simulate the response of plants to climate change (White et al., 1997; Chuine, 2000; van Oort et al., 2011), explain seasonal changes in the CO_2 cycle (Baldocchi et al., 2001) and study inter-annual CO_2 flux variation (White and Nemani, 2003).

Crop phenology plays an important role in crop development and yield (Zhang et al., 2008; Andrej et al., 2011; Tao et al., 2012), therefore, the simulation of crop development is important in many crop simulation models (Chuine et al., 1999; Streck et al., 2007). Simulating and predicting the processes of crop phenology has great importance (White et al., 1997; Chuine, 2000; Zalud and Dubrovsky, 2002). Many sub-models or parameters within a model simulate phenology at different stages of growth. Existing crop phenological models use quite different methods to simulate the way crops respond to differences in climate. They use different parameters and model the effect of day length differently. Current phenological models have generally been developed for specific locations and specific cultivars. However, the uncertainties in simulating and predicting changes in crop phenology at a large scale in major crop producing regions of China and from different models have not yet been fully investigated. Our aim to (1) evaluate the use of the phenology models at a large scale; (2) compare the mechanisms of the five rice phenology models and investigate the uncertainties from them; and (3) investigate how rice phenology would change in major rice production regions with climatic change in future.

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http://dx.doi.org/10.1016/j.eja.2012.10.005

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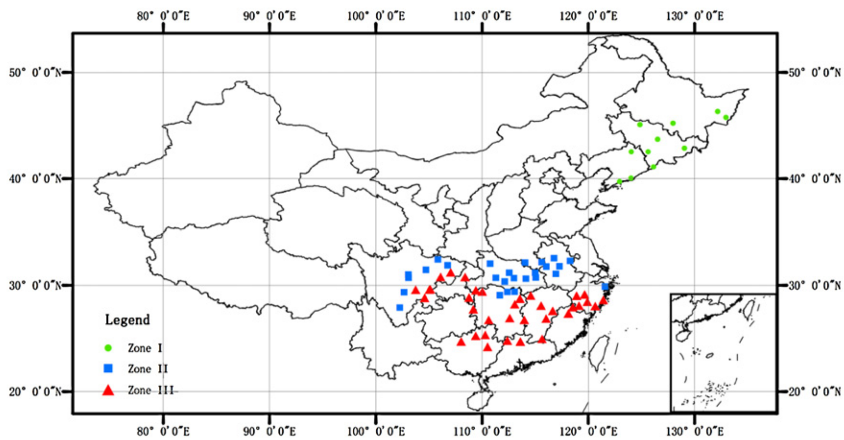

Fig. 1. Locations of study sites in China.

2. Materials and method

2.1. Study areas

We focused on two of major rice production regions of China, the northeast China Plain and the middle and lower reaches of Yangtze River where single or double rice cropping systems are popular. The single-season rice cultivated area has been divided into three zones, northeastern China (zone I), north of the Yangtze River (zone II) and south of the Yangtze River (zone III). The double rice cultivation area has been divided into two zones: north of the Yangtze River (zone II) and south of the Yangtze River (zone III) (Fig. 1).

2.2. Data

Data on rice phenology were obtained from the agro-meteorological experimental stations of the China Meteorological Administration (CMA) (Fig. 1). The data were collected in a total of 31, 32, and 42 stations for early-rice, late-rice and single season rice, respectively, from 1990 to 2009. Transplanting date, heading date and maturity date for each station were concluded in the dataset.

Mean, maximum, and minimum temperatures from 1980 to 2009 were obtained from CMA. Day length is a function of latitude and day of year (Spitters, 1986). The future climate scenarios used for this research were constructed from a regional climate model called the Regional Integrated Environmental Model System (RIEMS, Xiong et al., 2009).

2.3. Methods

2.3.1. Descriptions of the rice phenology models

Five widely used, easily accessible and well-documented rice growth simulation models, i.e. CERES-Rice, ORYZA2000, RCM, Beta Model and SIMRIW, were applied in this research. Each model used different parameters and methods to simulate rice phenology. In order to compare these five models, the growth stage in these models has been unified. The stage from transplanting date to heading date is defined as vegetative growth period (VGP); the stage from heading date to maturity date is defined as reproductive growth stage (RGP). The developmental index (DVI) is defined as 0.1 at transplanting, 1 at heading and 2 at maturity respectively. So DVI of VGP is from 0.1 to 1, and DVI of RGP is from 1 to 2. The value of DVI is calculated by summing the developmental rate (DVR) with respect to time:

$$DVI_t = \sum_{i=0}^{i=t} DVR_i \tag{1}$$

DVI_t is the developmental index at day t, and DVI_i is the developmental rate on the ith day from transplanting. And models are discussed briefly below.

The CERES-Rice model (Alocija and Ritchie, 1988; Jones et al., 2003) has been used extensively to assess crop yields under current conditions; CERES-Rice has also been used to study climate change over a wide range of environments, including in China (Parry et al., 1999; Tao et al., 2008b). In this model, daily thermal time (DTT) is used to describe the process of rice development. VGP completes when the accumulation of DTT reaches a threshold ($P1$); RGP completes when the accumulation of DTT reaches a threshold ($P5$). In order to compare these five models, the variable use to describe rice development has been unified to DVR, the equations form has been convert as follows:

$$DVR = DTT \cdot \frac{FDL}{P1} \quad for \quad 0 < DVI \le 1 \tag{2}$$

$$DVR = \frac{DTT}{P5} \quad for \quad 1 < DVI \le 2 \tag{3}$$

DTT was calculated as follows:

$$\begin{cases} DTT_i = 0 \quad for \quad T_{\max} \le T_{base} \quad or \quad T_{\min} \ge T_{high} \\ DTT_i = \dfrac{T_d - T_{base}}{24} \quad for \quad T_{\max} > T_{opt} \quad or \quad T_{\min} < T_{base} \end{cases} \tag{4}$$

T_{opt} is the optimum temperature, T_{high} is a critical high temperature for crop development, T_{base} is the base temperature. $T_{\min}$ and $T_{\max}$ are the daily minimum and maximum temperatures, T_d is hourly temperature, h is the hour of the day, T_d is calculated by $T_{\min}$ and $T_{\max}$:

$$T_d = \frac{T_{\min} + T_{\max}}{2} + (T_{\max} - T_{\min}) \cdot \sin \frac{[3.14/(12 \cdot h)]}{2} \tag{5}$$

$$\begin{cases} T_d = T_{base} \quad for \quad T_d < T_{base} \\ T_d = T_{opt} - (T_d - T_{opt}) \quad for \quad T_d > T_{opt} \end{cases} \tag{6}$$

factor of day length (FDL) was calculated as follows:

$$FDL = \left[1 + \frac{P2R}{136} \times (DL_k - DL_c)\right]^{-1} \tag{7}$$

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DL_k is daily mean day length, DL_c is the critical day length, $P2R$ is photoperiod sensitivity parameter.

In the ORYZA2000 (Kropff et al., 1994; Bouman et al., 2001) model, daily increments in developmental time (DTU) are used to describe the development of rice in this model. When the accumulation of DTU has reached the threshold (DVRI), VGP has been completed; when the accumulation of DTU has reached the threshold (DVRR), RGP has been completed. And the equations form has been convert as follows:

$$DVR = DTU \cdot \frac{FDL}{DVRI} \quad for \quad 0 < DVI \le 1 \tag{8}$$

$$DVR = \frac{DTU}{DVRR} \quad for \quad 1 < DVI \le 2 \tag{9}$$

DTU is calculated as:

$$DTU = \sum_{h=1}^{24} (HD) \tag{10}$$

$$\begin{cases} HD=0 \quad for \quad T_d \le T_{base} \quad or \quad T_d \ge T_{high} \\ HD=\dfrac{T_d - T_{base}}{24} \quad for \quad T_{base} < T_d \le T_{opt} \\ HD=\dfrac{[T_{opt} - (T_d - T_{opt}) \times (T_{opt} - T_{base})/(T_{high} - T_{opt})]}{24} \quad for \quad T_{opt} < T_d < T_{high} \end{cases} \tag{11}$$

HD is hourly increments in developmental age. And T_d is calculated from $T_{\min}$ and $T_{\max}$ according to the relation:

$$T_d = \frac{T_{\min} + T_{\max}}{2} + \frac{(T_{\max} - T_{\min})\cos[0.2618(h-14)]}{2} \tag{12}$$

FDL are calculated as:

$$FDL = 1 - (DL_k - DL_c) \times PPSE \tag{13}$$

PPSE is photoperiod sensitivity parameter.

The Rice Clock Model (RCM) (Gao et al., 1992) describes a base model covering the entire stage of rice development and uses daily mean temperature and day length data to calculate the daily development of rice.

$$DVR = \exp(k)\left(\frac{T - T_{base}}{T_{opt} - T_{base}}\right)^P \left(\frac{T_{high} - T}{T_{high} - T_{opt}}\right)^Q \exp[G(DL_k - DL_c)] \tag{14}$$

$$\begin{cases} T = T_{base} \quad for \quad T < T_{base} \\ T = T_{high} \quad for \quad T > T_{high} \end{cases} \tag{15}$$

$$DL_k = DL \quad for \quad DL_k < DL_c \tag{16}$$

T is the daily mean temperature, k, P, Q and G are empirical constants, during RGP, $G = 0$ was assumed.

Yin (Yin et al., 1995; Yin and Kropff, 1996) introduced the nonlinear Beta Model to rice development modeling:

$$DVR = \exp(\mu)(T - T_{base})^{\alpha}(T_{high} - T)^{\beta} \cdot DL_k^{\delta}(24 - DL_k)^{\varepsilon} \quad for \quad 0 < DVI \le 1 \tag{17}$$

$$DVR = \exp(\mu)(T - T_{base})^{\alpha}(T_{high} - T)^{\beta} \quad for \quad 1 < DVI \le 2 \tag{18}$$

μ, α, β, and ε are empirical constants.

In the Simulation Model for Rice-Weather Relationship (SIMRIW) (Horie et al., 1995a,b), the phenological development is described by using the developmental index (DVI). DVR from transplanting to heading ($0 < DVI < 1$) is calculated as follows:

$$\begin{cases} DVR = \dfrac{\{1 - \exp[B(DL_k - DL_c)]\}}{G_v\{1.0 + \exp[-A(T - T_h)]\}} \quad for \quad DL_k \le DL_c \\ DVR = 0 \quad for \quad DL_k > DL_c \end{cases} \tag{19}$$

T_h is the temperature at which DVR is half the maximum rate at the optimum temperature (°C), G_v is the minimum number of days required for heading, A, B are empirical constants.

The following equation is used to describe the rate of rice development from heading to maturity ($1 < DVI \le 2$)

$$DVR = \frac{\{1 - \exp[-K_r(T - T_{cr})]\}}{G_r} \tag{20}$$

where G_r is the minimum number of days for grain-filling period K_r and T_{cr} are empirical constants.

2.3.2. Calibration and validation

Phenological data during 1990–2000 at each station were used to calibrate the parameters of all five models. Because rice has different temperature response function before and after heading, the parameters were estimated separately for VGP and RGP. Heading date and maturity date of rice were simulated by these five models. And the estimated parameters in each model were show in Table 1. Statistical analysis was done with the nonlinear regression procedure (Proc NLIN) in Statistical Analysis System (SAS, SAS Institute Inc., Cary, NC, USA).

Phenological data from 2001 to 2009 was used for validation. We evaluated the accuracy of models by calculating the root mean square error (RMSE) between the observed and simulated value for both heading date and maturity date:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Simulated_i - Observed_i)^2}{n}} \tag{21}$$

where n is the number of comparisons.

Both calibration and validation work has been done for early rice, late rice and single season rice in each zone respectively.

3. Results

3.1. The performance of models in simulating regional rice phenology

Each model had differences in structure and in the way it was initially set up as well as having differences in the parameters used in the model. These differences resulted in a wide variety of results and sensitivities in the models. The five models were calibrated and validated in different zones; we used a set of optimal parameters for each simulated growing season in each zone. All of the five models simulated rice development and phenology reasonably well (Fig. 2). The RMSE of the simulated heading date varied from 1.16 to 4.46 days (mean = 2.97), and the RMSE of the simulated maturity date simulation varied from 2.18 to 6.69 days (mean = 3.62) (Table 2).

But the performances of these models varied from zone to zone. For early rice in zone II, CERES-Rice and ORYZA2000 performed better. For early rice in zone III and for late rice in zone II the Beta Model performed better. For late rice in zone III and for single season rice in zone II RCM performed better. For single season rice in zone I and for single season rice in zone III SIMRIW performed better.

Table 1
Major parameters in the five rice phonological models.

	VGP Growth index (0–1)	RGP Growth index (1–2)
CERES-Rice	*P1*: the threshold of DTT for VGP DL_c: critical day length *P2R*: photoperiod sensitivity parameter	*P5*: the threshold of DTT for RGP
ORYZA2000	DVRI: the threshold of DTU accumulation for VGP PPSE: photoperiod sensitivity parameter DL_c: critical day length	DVRR: the threshold of DTU accumulation for RGP
RCM	k: empirical constants P: empirical constants Q: empirical constants G: empirical constants DL_c: critical day length	k: empirical constants P: empirical constants Q: empirical constants
Beta Model	μ: empirical constants α: empirical constants β: empirical constants δ: empirical constants ε: empirical constants	μ: empirical constants α: empirical constants β: empirical constants
SIMRIW	DL_c: critical day length T_h: the temperature at which DVR is half the maximum rate at the optimum temperature G_v: the minimum number of days required for heading A: empirical constants B: empirical constants	G_r: the minimum number of days for grain-filling period K_r: empirical constants T_{cr}: empirical constants

Table 2
Validation results of the rice phenology models in different zones. Zone I_S represents single season rice at Northeast China; zone II_E represents early rice at North of Yangtze River; zone II_S represents single season rice at North of Yangtze River; zone II_L represents later rice at North of Yangtze River; zone III_E represents early rice at South of Yangtze River; zone III_S represents single season rice at South of Yangtze River; Zone III_L represents later rice at South of Yangtze River.

Zone	Model	Heading date				Maturity date			
		Mean (days)	Std (days)	R^2	RMSE (days)	Mean (days)	Std (days)	R^2	RMSE (days)
Zone I_S	CERES-RICE	217.40	1.48	0.90**	1.24	257.91	7.69	0.82**	6.15
	ORYZA2000	217.92	1.46	0.89**	1.60	259.01	7.34	0.82**	5.27
	RCM	216.08	1.47	0.30	2.26	262.03	3.78	0.50	3.71
	Beta Model	215.41	1.37	0.17	2.65	262.27	3.42	0.35	4.05
	SIMRIW	216.91	1.39	0.51	1.84	262.11	2.35	0.75**	2.54
Zone II_E	CERES-RICE	175.91	3.57	0.55	3.46	200.49	3.53	0.79**	2.18
	ORYZA2000	176.02	3.34	0.59	3.24	199.81	3.67	0.81**	2.18
	RCM	174.87	6.09	0.64	4.46	200.45	4.87	0.56*	3.98
	Beta Model	175.00	4.42	0.65	3.41	199.46	3.87	0.68**	3.01
	SIMRIW	173.78	2.88	0.51	3.78	199.22	3.10	0.82**	2.30
Zone II_S	CERES-RICE	220.01	2.18	0.35	2.37	255.88	7.52	0.89**	3.52
	ORYZA2000	219.70	2.12	0.37	2.49	255.17	7.70	0.89**	3.68
	RCM	221.80	2.13	0.52	1.84	257.30	4.90	0.89**	2.82
	Beta Model	221.47	2.12	0.45	1.86	256.42	4.04	0.85**	2.91
	SIMRIW	221.67	1.25	0.65*	1.16	257.91	3.67	0.90**	3.33
Zone II_L	CERES-RICE	255.50	3.38	0.67	3.29	293.53	7.20	0.71**	4.94
	ORYZA2000	255.64	3.38	0.67	3.27	291.60	6.95	0.75**	5.12
	RCM	255.57	3.17	0.58	3.63	294.63	4.55	0.72**	3.50
	Beta Model	255.57	3.37	0.60	3.57	295.20	3.78	0.73**	3.41
	SIMRIW	256.57	3.71	0.45	4.21	292.87	3.36	0.62*	3.99
Zone III_E	CERES-RICE	172.13	3.05	0.55	3.03	201.62	4.26	0.84**	2.60
	ORYZA2000	171.94	3.17	0.59	3.08	200.87	4.38	0.82**	2.53
	RCM	173.44	2.91	0.31	3.12	201.58	3.93	0.81**	2.50
	Beta Model	172.68	2.95	0.40	3.09	201.57	3.70	0.83**	2.27
	SIMRIW	173.61	3.93	0.68*	2.81	198.10	4.92	0.78**	3.88
Zone III_S	CERES-RICE	200.43	5.66	0.88**	3.54	236.22	7.72	0.89**	3.41
	ORYZA2000	201.63	5.64	0.89**	2.89	236.16	7.67	0.89**	3.46
	RCM	200.87	6.92	0.96**	2.58	235.43	7.28	0.87**	3.50
	Beta Model	201.30	5.76	0.92**	2.67	235.22	6.23	0.89**	3.00
	SIMRIW	202.91	4.97	0.80*	3.48	235.70	5.98	0.89**	2.79
Zone III_L	CERES-RICE	263.33	4.50	0.44	4.30	298.25	9.77	0.77**	6.57
	ORYZA2000	262.78	4.23	0.45	4.00	296.19	9.47	0.74**	6.69
	RCM	261.79	2.25	0.67	2.65	297.96	4.36	0.79**	2.99
	Beta Model	261.66	2.14	0.68	2.66	297.02	4.13	0.72**	3.47
	SIMRIW	260.62	3.68	0.28	4.46	296.53	3.12	0.45	4.54

* $p < 0.05$.
** $p < 0.01$.

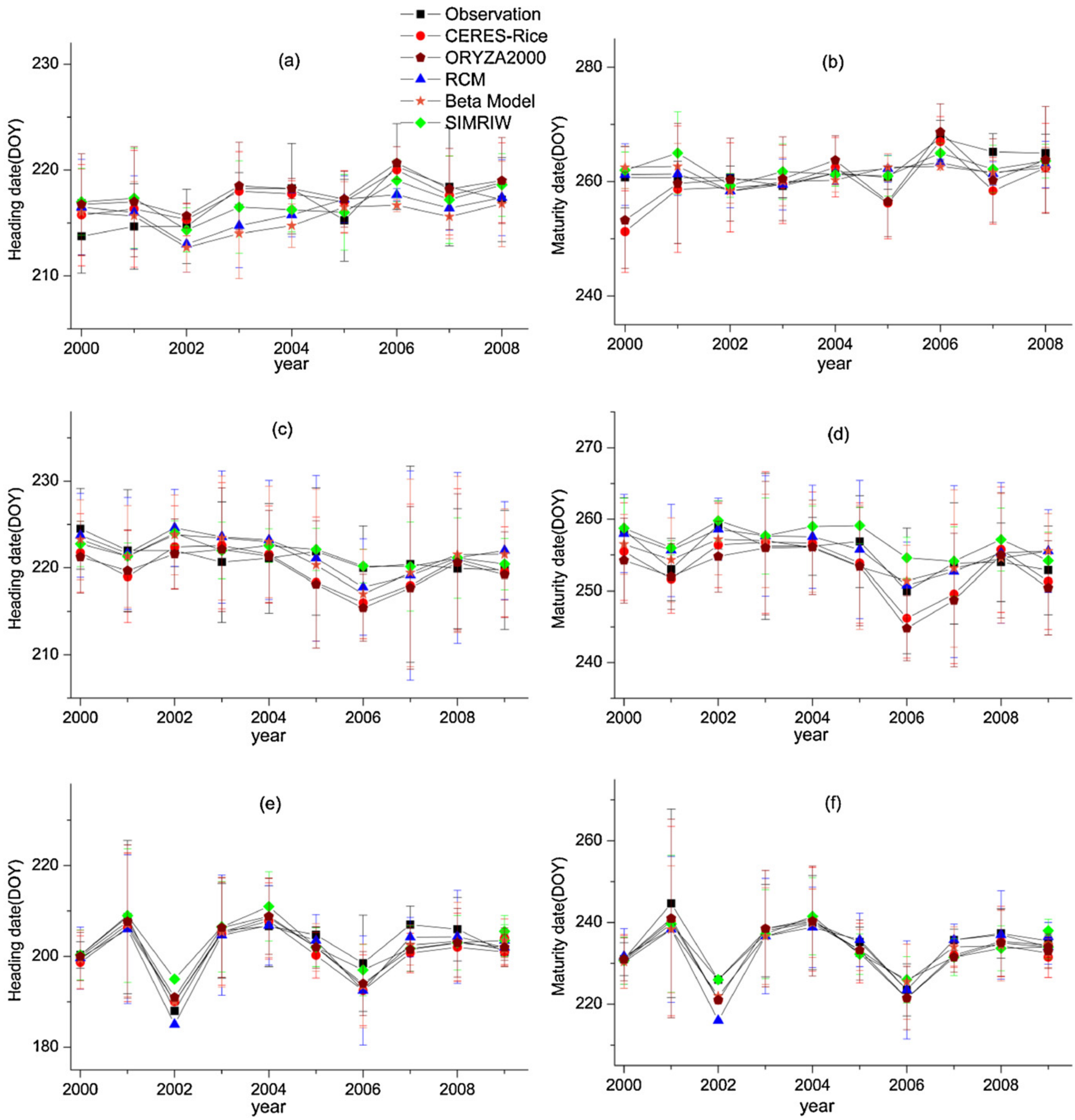

Fig. 2. Simulated and observed rice heading dates (a, c and e) and maturity dates (b, d and f) for single season rice in zones I, II, and III, respectively.

3.2. The response mechanism of rice development to temperature in models

We found these models have some differences in simulating the response of rice development rate to temperature (Fig. 3). T_{opt} of rice is generally between 28 and 32 °C. When the temperature was between T_{base} and T_{opt}, the differences in the simulated rice development rate by these models were relatively small. All models showed the rice development rate increased with temperature but at different rates. However, when daily mean temperature was above T_{opt}, the simulated rice development rate varied largely among these models. When daily mean temperature was above T_{opt}, the simulated rice development rate decreased linearly when using the CERES-Rice and ORYZA2000 models. It decreased sharply and became 0.0 when the daily mean temperature changed from T_{opt} to the maximum temperature (T_{high}) when using the RCM and the Beta models. The simulated rice development rate provided by the SIMRIW model was quite different from that of the other four models; it was relatively small when T_{mean} was less than T_{opt}; however it stayed at that level under T_{opt} when T_{mean} changed from T_{opt} to T_{high}. Because both climate and the parameters in different zones are different with the same model, the simulated maximum development rate by each model could be quite different in different zones. The development rate of single rice was generally smaller than that of early rice and late rice.

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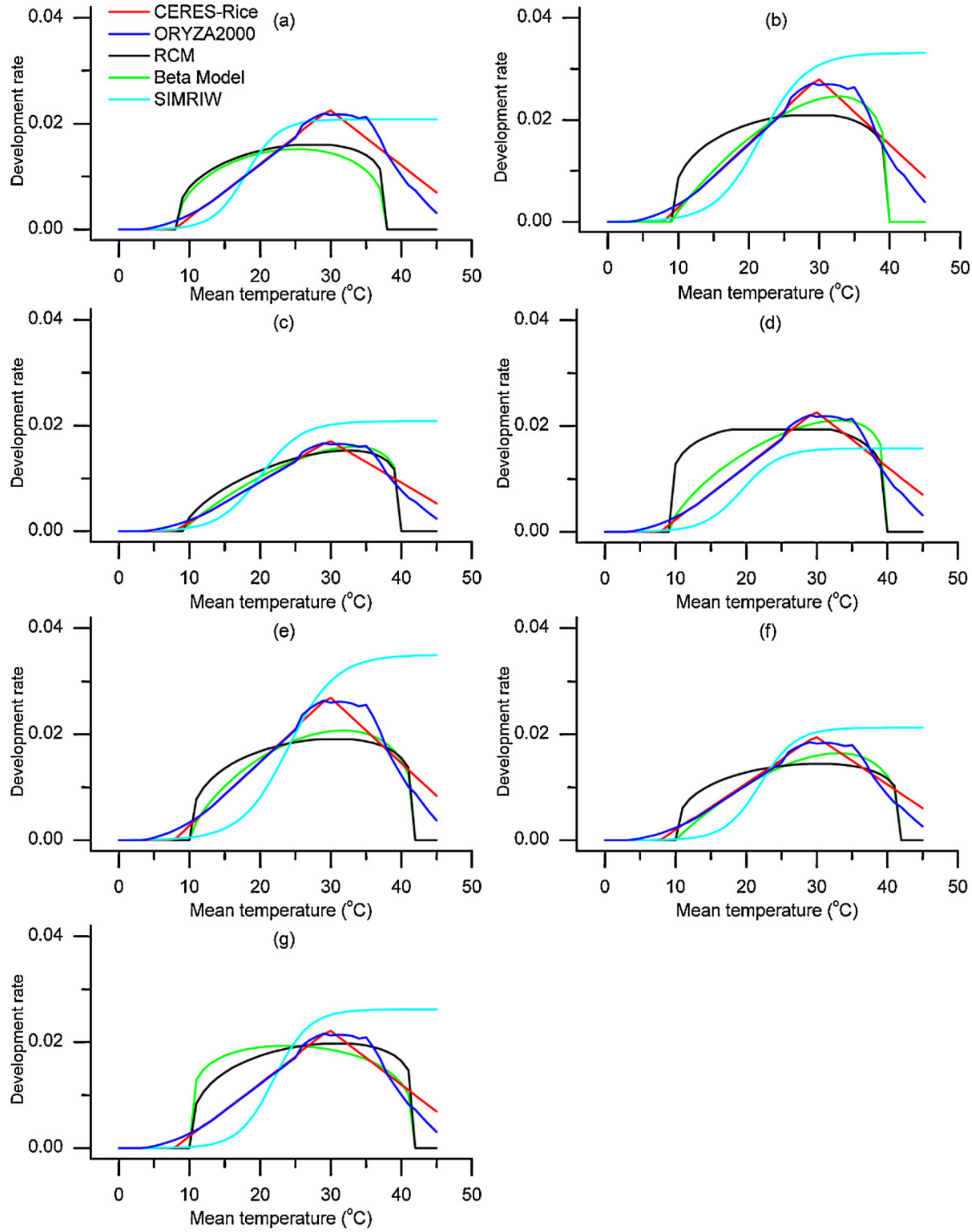

Fig. 3. Comparison of the response of rice development rate to temperature in five rice phenological models. Early rice in zone II (a) and zone III (b), late rice in zone II (c) and zone III (d), single season rice in zone I (e), zone II (f), and zone III (g).

3.3. Uncertainties of models in simulating rice phenological changes caused by climate change

After the five models were validated, the models were run under baseline climatic conditions (1981–2000) and future climate conditions (2021–2040) for each zone. Based on the climate scenarios from the regional climate model RIEMS, the growing season T_{mean} for rice was projected to increase by about 1.30 °C, 1.12 °C, and 1.15 °C in zone I, II and III, respectively, however with larger variability (Fig. 4a). For single season rice in zone I, these models projected the vegetative growing period to be prolonged by about 0.38–1.77 days, and CERES-Rice and ORYZA2000 projected a shorter growing period (GP) from transplanting to maturity while RCM, Beta Model and SIMRIW projected a prolonged GP (Table 3). All five models projected a shorter future VGP and GP for zones II and III (Fig. 4). Specifically, when compared to 1981–2000, the VGP and GP are projected to be shortened by about 0.62–3.17 and 0.45–5.78, respectively, during 2021–2040 (Table 3).

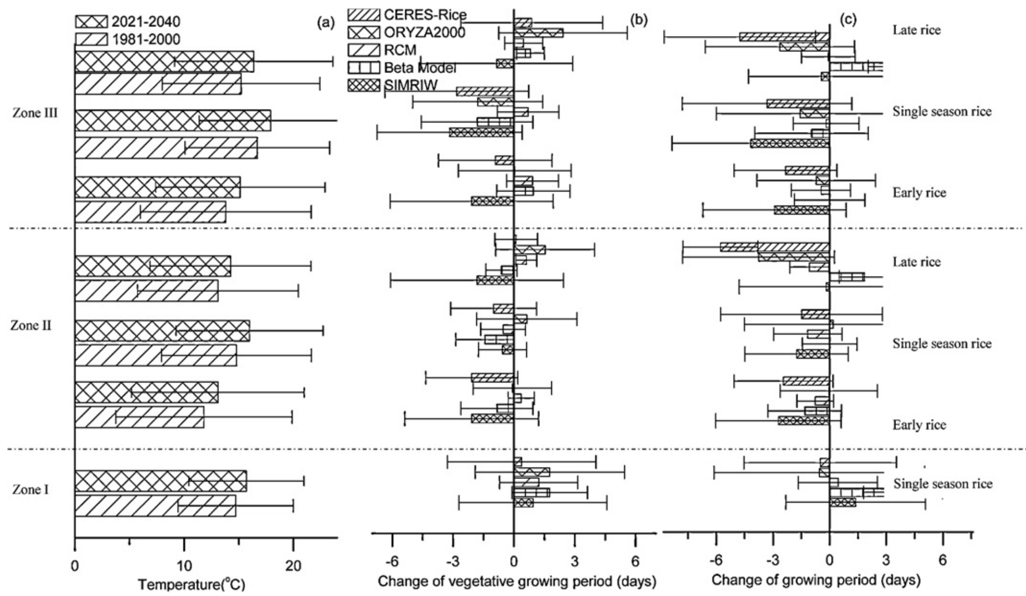

Fig. 4. Projected change in mean temperature during the growing period (a), and simulated changes in the vegetative growing period (b) and the growing period (c) under the future climate scenarios.

Table 3
Change of rice vegetative growing period and growing period under the future climate scenarios in different zone. Zone I_S means single season rice at Northeast China; zone II_E means early rice at North of Yangtze River; zone II_S means single season rice at North of Yangtze River; zone II_L means later rice at North of Yangtze River; zone III_E means early rice at South of Yangtze River; zone III_S means single season rice at South of Yangtze River; zone III_L means later rice at South of Yangtze River.

Zone	Model	Change of vegetative growing period		Change of growing period	
		Mean (days)	Std (days)	Mean (days)	Std (days)
Zone I_S	CERES-RICE	0.38	3.66	−0.50	4.04
	ORYZA2000	1.77	3.68	−0.54	5.58
	RCM	1.22	1.93	0.44	2.09
	Beta Model	1.76	1.86	3.88	2.09
	SIMRIW	0.94	3.64	1.38	3.70
Zone II_E	CERES-RICE	−2.08	2.27	−2.44	2.62
	ORYZA2000	−0.08	1.93	−0.04	2.57
	RCM	0.36	0.64	−0.76	0.97
	Beta Model	−0.84	1.77	−1.32	1.95
	SIMRIW	−2.08	3.30	−2.71	3.32
Zone II_S	CERES-RICE	−1.00	2.11	−1.48	4.29
	ORYZA2000	0.64	2.47	0.18	4.69
	RCM	−0.53	1.11	−1.16	1.82
	Beta Model	−1.44	1.44	0.00	1.44
	SIMRIW	−0.56	1.19	−1.75	2.74
Zone II_L	CERES-RICE	0.11	1.05	−5.78	1.99
	ORYZA2000	1.54	2.44	−3.77	4.02
	RCM	0.62	0.51	−1.08	1.04
	Beta Model	−0.62	0.77	1.85	1.34
	SIMRIW	−1.82	4.26	−0.18	4.60
Zone III_E	CERES-RICE	−0.92	2.80	−2.33	2.71
	ORYZA2000	0.04	2.79	−0.71	3.14
	RCM	0.92	1.28	−0.46	1.56
	Beta Model	0.96	1.81	0.00	1.87
	SIMRIW	−2.09	4.02	−2.91	3.79
Zone III_S	CERES-RICE	−2.82	3.54	−3.32	4.49
	ORYZA2000	−1.78	3.20	−1.57	4.43
	RCM	0.70	1.51	−0.19	1.73
	Beta Model	−1.81	2.75	−0.96	3.01
	SIMRIW	−3.17	3.58	−4.17	4.17
Zone III_L	CERES-RICE	0.88	3.50	−4.75	4.01
	ORYZA2000	2.42	3.17	−2.63	3.95
	RCM	0.48	0.94	−0.07	1.41
	Beta Model	0.81	0.68	3.44	1.40
	SIMRIW	−0.85	3.75	−0.45	3.85

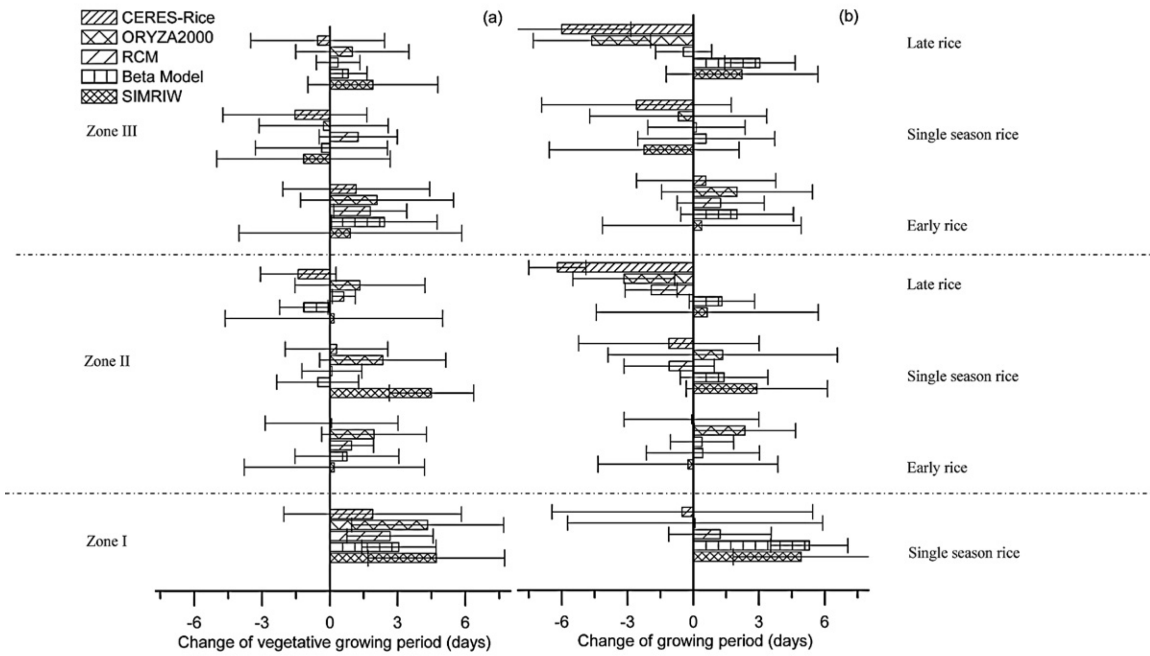

Fig. 5. Simulated changes in the vegetative growing period (a) and the growing period (b) under the future climate scenarios with the transplanting date advanced by one week.

The estimates of rice phenology in future climate had a relatively large range of variation. This was caused by the fact the models used different methods to simulate the response mechanisms and degrees of rice development at different temperatures (Fig. 4). CERES-Rice generally shortened the simulated GP in response to climate change, because the rice development rate was modeled to decrease linearly at higher temperatures. The Beta Model simulated GP in response to climate change by either generally shortening the GP less or by prolonging the GP more; this was because the Beta Model was designed to decrease the rice development rate more sharply at higher temperatures. In contrast, the SIMRIW model simulated a shorter VGP and GP in response to climate change, because the rice development rate was modeled to be more sensitive to temperatures below T_{opt}, and was modeled to not be sensitive to temperatures above T_{high} at all. SIMRIW simulated the rice development rate to increase faster for single season rice and early rice

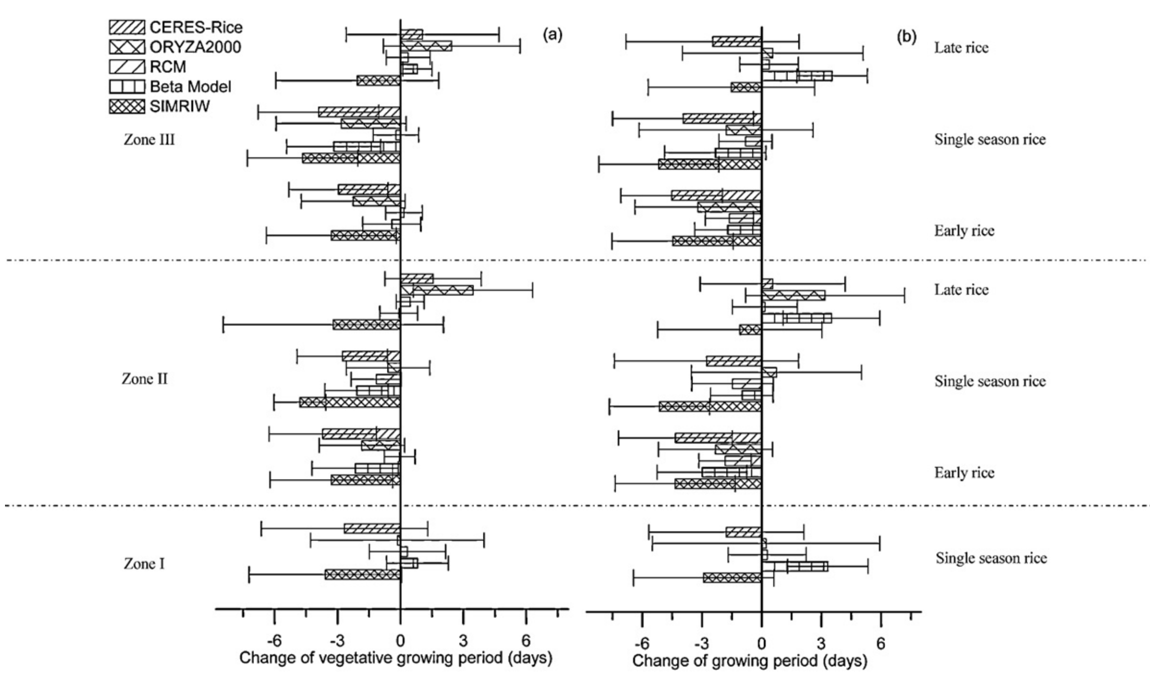

Fig. 6. Simulated changes in the vegetative growing period (a) and the growing period (b) under the future climate scenarios, with transplanting date delayed by one week.

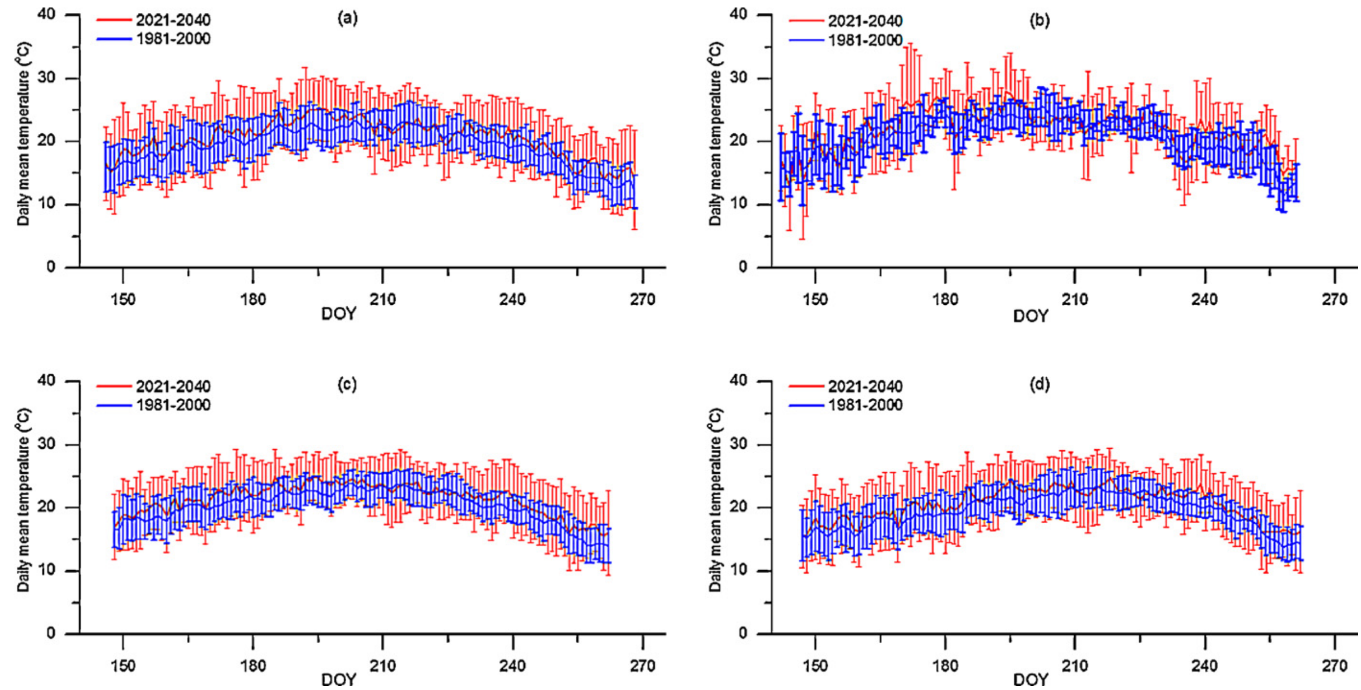

Fig. 7. Daily mean temperatures and its standard deviation over the growing period during 1981–2000 and 2021–2040 at Baoqing station (a), Yongji station (b), Meihekou station (c) and Yanji station (d) in zone I.

in zones II and III, than the other models (Fig. 3), so in these cases the simulated VGP and GP are shortened more by SIMRIW than by the other models.

3.4. Sensitivity of rice phenological changes to transplanting date

When the transplanting date was modeled to advance by one week, the simulated VGP was generally shortened in all three zones (Fig. 5); however the simulated GP was prolonged in some cases, except the simulations in zones II and III by CERES-Rice and ORYZA2000. An early simulated transplanting could prolong the duration of the GP. This was especially true for early rice in zone III where both the durations of VGP and GP were prolonged. Taking single season rice in zone I as an example, VGP was obviously prolonged for about 1.9–4.3 days. The RCM, Beta Model and SIMRIW models resulted in a prolonged simulated GP. In using the CERES-Rice and ORYZA2000 models, the simulated GP was more prolonged, in contrast to simulated VGP which was prolonged less or even shortened a little. When the transplanting date was delayed by one week (Fig. 6), the GP duration was generally shortened by about 0.81–5.16 days, which was the opposite of the results when the transplanting date was advanced.

4. Discussion

4.1. Response of rice phenology to extreme temperature and its simulation

Previous modeling studies have generally shown rice crop phenology will be advanced and GP could be shortened in the future as a result of climatic warming (Chen et al., 2005; Karlsen et al., 2009). In this study, we found T_{mean} was projected to increase during growing period (Fig. 7); however the heading date and maturity date of single season rice were projected to be delayed in zone I. Further analyses showed this delay was due to the projected increase in temperature variability in zone I. Most of the stations in zone I have been found increase in temperature variability. For example, the time series of daily T_{mean} and its standard deviation during the entire growing period of Baoqing station (46°19′N, 132°10′E), Yongji station (43°42′N, 126°31′E), Meihekou station (42°31′N, 125°37′E), Yanji station (42°52′N, 129°3′E) were presented as both a baseline and future prediction (Fig. 7). Obviously, although T_{mean} during growing period could increase in the future, more extreme temperatures could occur in future. Extremely high or low temperatures can delay rice development rate as shown in all the phenology models (Fig. 3).

We further modified the future scenarios data, keeping the same mean but reducing standard deviation to be half. The modified future scenarios have been used to simulate the change of vegetative growing period and growing period in zone I. The results showed that under the modified scenarios, the heading date and maturity date of single season rice were projected to be advanced in zone I (Fig. 8). Therefore, it is the more frequent extreme temperatures with climate warming that delay development rate of rice.

4.2. Change of rice phenology and its sensitivity to planting date

Previous studies showed farmers could adapt to the impacts of climate change on crop phenology and productivity by shifting planting dates (e.g., Tao and Zhang, 2010). Here we investigated the sensitivity of rice phenology to transplanting date. In comparing the simulated results with the shift in transplanting date shown in Fig. 3, the simulated GP was mainly prolonged if the transplanting date advanced by one week, advancement of transplanting date by one week delayed maturity except for late rice (Table 4). Early rice is mainly transplanted during April–May; single season rice is mainly transplanted during May–June. The daily mean temperature during these months was below T_{opt}, and the advancing of the transplanting date will prolong the duration of low temperatures

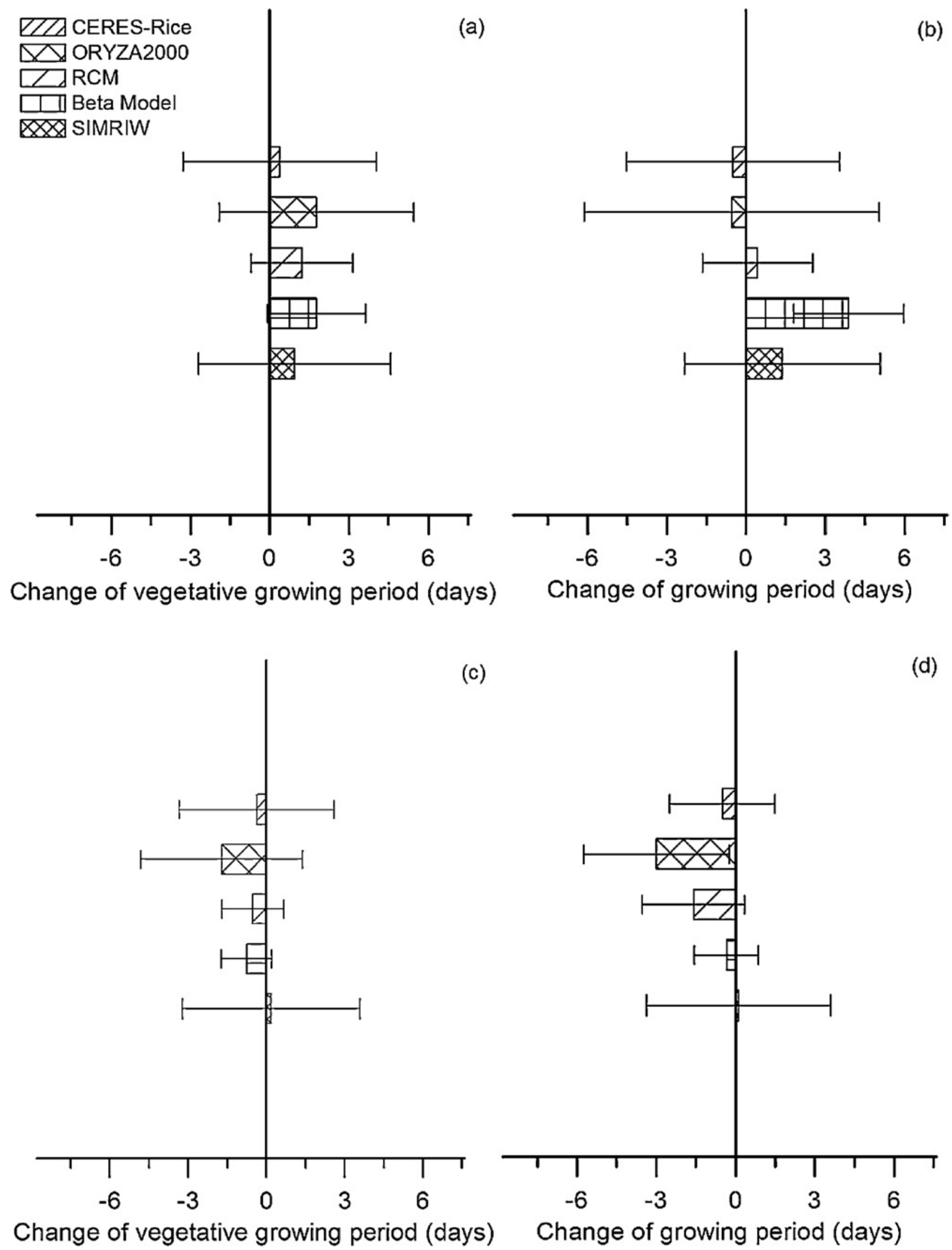

Fig. 8. Changes in the vegetative growing period and the growing period under the future climate scenarios (a and b) and modified future climate scenarios (c and d) in zone I.

during rice development (Shimono, 2011), and decrease the developmental rate of rice. But since the transplanting date of late rice was between July and August, when the daily mean temperature is high and even exceeds T_{opt} of rice, advancement of the transplanting date will decrease the mean temperature during the rice growing period, which can increase the developmental rate of rice during this time period.

4.3. Uncertainties in rice phenology simulations

The response mechanisms of rice development rates are different in each of the models, and their performances in simulating crop phenology and their response to climate change varied in different scenarios (Rotter et al., 2011). As a result, their estimates on the response of crop phenology to climate change vary widely. For example, the CERES-Rice and ORYZA2000 models have similar mechanisms to simulate rice phenology; their simulations of the response of the crop developmental rate to climate change were different from other models. Particularly, when temperature is extremely low or high, there are distinctively different responses among the models, which cause large deviations in the models simulation results.

In most crop phenology simulation studies, usually one model has been chosen, and the simulation has been done at specific stations (Van et al., 2003; de Wit et al., 2005). Our results found that there were large differences between models in each zone. The development rate simulated by each model was different, and the best model in each zone was different. So, different models should be chosen for different zones. The uncertainties in simulating crop phenology should be paid more attention.

Table 4
Change of rice vegetative growing period and growing period under the future climate scenarios due to advanced and delayed transplanting. Zone I_S means single season rice at Northeast China; zone II_E means early rice at North of Yangtze River; zone II_S means single season rice at North of Yangtze River; zone II_L means later rice at North of Yangtze River; zone III_E means early rice at South of Yangtze River; zone III_S means single season rice at South of Yangtze River; zone III_L means later rice at South of Yangtze River.

		Transplanting date advanced by one week		Transplanting date delayed by one week	
		Vegetative growing period (days)	Growing period (days)	Vegetative growing period (days)	Growing period (days)
Zone I_S	CERES-RICE	1.53	0.00	−3.04	−1.28
	ORYZA2000	2.56	0.62	−1.91	0.75
	RCM	1.44	0.78	−0.89	−0.17
	Beta Model	1.29	1.41	−0.95	−0.57
	SIMRIW	3.78	3.55	−4.52	−4.29
Zone II_E	CERES-RICE	2.16	2.36	−1.63	−1.89
	ORYZA2000	2.04	2.40	−1.76	−2.28
	RCM	0.60	1.16	−0.40	−1.08
	Beta Model	1.60	1.76	−1.32	−1.68
	SIMRIW	2.28	2.47	−1.22	−1.64
Zone II_S	CERES-RICE	1.30	0.37	−1.77	−1.29
	ORYZA2000	1.70	1.17	−1.24	0.56
	RCM	0.63	0.06	−0.63	−0.31
	Beta Model	0.91	1.41	−0.66	−1.00
	SIMRIW	5.06	4.66	−4.23	−3.39
Zone II_L	CERES-RICE	−1.51	−0.42	1.44	6.33
	ORYZA2000	−0.21	0.60	1.92	6.95
	RCM	0.00	−0.85	−0.15	1.23
	Beta Model	−0.54	−0.54	0.53	1.65
	SIMRIW	2.00	0.82	−1.38	−0.92
Zone III_E	CERES-RICE	2.08	2.92	−2.04	−2.19
	ORYZA2000	2.05	2.71	−2.29	−2.50
	RCM	0.88	1.71	−0.75	−1.17
	Beta Model	1.46	2.00	−1.38	−1.71
	SIMRIW	3.00	3.30	−1.21	−1.56
Zone III_S	CERES-RICE	1.27	0.73	−1.09	−0.63
	ORYZA2000	1.51	0.88	−1.04	−0.22
	RCM	0.56	0.33	−0.93	−0.63
	Beta Model	1.44	1.56	−1.37	−1.37
	SIMRIW	2.01	1.93	−1.49	−0.99
Zone III_L	CERES-RICE	−1.41	−1.25	0.18	2.28
	ORYZA2000	−1.42	−1.99	0.02	3.19
	RCM	−0.11	−0.37	−0.11	0.44
	Beta Model	0.00	−0.41	−0.01	0.09
	SIMRIW	2.76	2.68	−1.20	−1.08

5. Conclusions

The uncertainties associated with the five rice phenological models/modules in simulating and predicting rice phenological changes in the major rice production regions of China have been investigated. These models can simulate rice phenology reasonably well over a large area when simulating rice phenological development after they were calibrated. However, the relative performance of these models is different in different zones.

Also different rice phenological models have different mechanisms. The input data of all the five models include temperature, but some use $T_{\min}$ and $T_{\max}$, some use T_{mean}, and the equations used are quite different. The simulated changes in rice phenology by these models were generally consistent when temperature was below the optimum temperature for growing rice, with different rates of growth. However, their simulations of the responses of rice development were largely different when temperatures exceeded the optimum temperature.

Under future climate scenarios, rice growing duration generally shortened by about 0.45–5.78 days as temperature rose. But in northeastern China, because of increased temperature variability, the length of the growing season of single season rice could be prolonged. We concluded the simulations of the response of rice development rates at above optimum temperatures, and with increased temperature variability, should be improved in further studies.

Acknowledgments

This study was supported by the National Key Programme for Developing Basic Science (Project Number 2010CB950902), and the strategic pilot scientific projects of the Chinese Academy of Science (Project Number XDA05090308), China. F. Tao acknowledges the support of the “Hundred Talents” Program from the Chinese Academy of Sciences. Many thanks are due to Dr. Upendra Singh (IFDC, USA) for his help with the phenology sub model of CERES-Rice. We acknowledge the phenological and climate data obtained from the Chinese Meteorological Administration was used in the study.

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Please cite this article in press as: Zhang, S., Tao, F., Modeling the response of rice phenology to climate change and variability in different climatic zones: Comparisons of five models. Eur. J. Agron. (2012), http://dx.doi.org/10.1016/j.eja.2012.10.005