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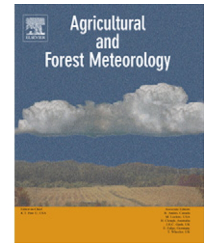

Non-stationary thermal time accumulation reduces the predictability of climate change effects on agriculture

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ARTICLE INFO

Article history:
Received 28 August 2007
Received in revised form
15 April 2008
Accepted 15 April 2008

Keywords:
Phenology
Lowland rice
Thermal time accumulation
Observed trend
Model deficiency
Climate change

ABSTRACT

Current modeling studies on the impacts of climate change on agriculture widely assume that thermal time accumulation of crops during the growing season remains constant under various climate conditions. However, in this study, a 20-year single rice variety, experimental dataset indicates that the thermal time accumulation for the entire growing season is not constant. As a result, a crop model based on constant thermal time accumulation significantly underestimates the observed phenological trend exhibited over the two decades of research—despite comparably accurate simulations of short periods. This deviation can result in misleading yield simulations, whereas the model simulations, using observed phenology data, show a similar yield trend as the observation. This study casts serious doubt on the assumptions of constant thermal time accumulation made in previous modeling studies, and, moreover, it highlights the critical requirements needed to improve phenology simulations on a larger scale so that predictions of the eventual yield trends due to climate change can more accurately reflect the results of yield trends in reality.

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1. Introduction

Climate change induced by anthropogenic warming has a significant influence on agricultural production. The Intergovernmental Panel on Climate Change (IPCC, 2007) suggests that a reduction in crop yields would occur with minimal warming in the tropics, while in temperate latitudes yields would be projected to rise slightly from a small rise in temperature (1–3 °C depending on the crop), and then decrease in some regions with continued future warming.

Substantial efforts have been made to predicate the future crop yield trends due to climate constraints by using a coupled climate-crop model (Dhungana et al., 2006; Guerena et al., 2001; Matthews et al., 1997; Yao et al., 2007). An example of such a modeling approach has been presented by Yao et al. (2007) who predicted the lowland rice yield response with climate change in China by coupling the CERES-Rice model with a regional climate model. In Yao's study, a collection of 3–5 years of experimental rice data for each agro-ecological zone in China was used first. This served as a base to determine the crop genetic coefficients that would be considered constant in the following steps. Then the crop model calculated grain yields under potential water and nitrogen supplies based on the climate scenarios provided by the climate model. Finally, the potential impacts of climate change were assessed by comparing the simulated yields with those under a baseline

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doi:10.1016/j.agrformet.2008.04.007

climate scenario. The model suggested that a negative climatic impact on lowland rice yield would occur in China. A similar modeling approach was also adopted by other climate change studies (Krishnan et al., 2007; Xiong et al., 2007).

Under potential water and nitrogen supplies, modeling studies such as these suggest two main effects that could play key roles in crop development under future climate scenarios. The first, a positive effect, is the direct fertilization effects of rising CO_2 concentrations that would increase yields (Parry et al., 2004). The second, a negative effect, is primarily due to the temperature's influence on crop phenology (earlier flowering and a shortened growing season), resulting in substantial yield reductions (Kwak and Lee, 2006; Sadras and Monzon, 2006; Xiong et al., 2007).

Phenology simulation is based on thermal time accumulation in various crop models such as APSIM (Meinke et al., 1997), CERES (Ritchie et al., 1998), and ORYZA2000 (Bouman et al., 2001). In most previous simulation studies, these crop models were driven by an implicit assumption that thermal time accumulation for crops would remain constant under various climate conditions. Using this assumption, an advanced phenological events modeling projection would be obtained because of the more rapid accumulation of thermal time under higher temperature climate scenarios. Thus, this assumption should be recognized as a crucial component when determining phenological responses to climate change.

Therefore, in this study, an observed 20-year single lowland rice variety dataset is provided as an extreme test of this assumption. The comparison between the observed and modeled phenology and yields over the 20 years is conducted, using the ORYZA2000 lowland rice simulation model (Bouman et al., 2001). The ORYZA series of crop models have been widely applied to predict the effects of climate change on lowland rice production, and, therefore, served as a useful tool in this study as well (e.g. Krishnan et al., 2007; Kwak and Lee, 2006; Matthews et al., 1997).

2. Materials and methods

2.1. Data collection

The daily meteorological data used in this study were obtained from the Chinese Meteorological Administration (CMA). These include daily minimum and maximum temperatures, sunshine hours, vapor pressure, wind speed, and rainfall. Also, data series for increasing CO_2 concentration in China were downloaded from the World Data Center for Greenhouse Gases website (WDCGG, 2005).

Crop data were obtained from the Tonghua Agricultural Experimental Station operated by the CMA. The farm at the Tonghua station (41°40′N, 125°45′E) is located in a temperate, monsoon climate environment in China. Only single-season rice (for which the primary growing season is May–September) can be produced in this area. Field experiments were conducted at the Tonghua station from 1985 to 2005. Historical data on rice phenological events (including emergence, transplanting, panicle initiation, flowering, and physiological maturity dates), field-level yields, and management practices were collected as well. To minimize genetic factors, only one rice variety (Qiuguang) was included in this study. Qiuguang is a japonica, lowland rice variety that was introduced in China at the end of the 1970s, and has since been widely planted by farmers in northern China. In our field experiments, these crops were quite well managed by the use of irrigation, fertilization, and pesticides. These relatively effective agricultural management practices and the studying of only a single rice variety ensured that phenology and yield trends depended almost exclusively on the change in climate conditions. This long-term dataset provided us with a rare opportunity to examine the response of phenology and yield trends due to climate change.

2.2. ORYZA2000 model

The ORYZA2000 is an eco-physiological model that simulates the growth, development, and water balance of lowland rice; Bouman et al. (2001) describes the details of the ORYZA2000 model quite thoroughly in his study. Thus, for the purposes of this report, only a brief introduction regarding phenological simulation using the ORYZA2000 model is presented.

The commencement of each phenological stage is determined by thermal time accumulation using ORYZA2000. Daily thermal time is obtained using the relationship in Fig. 1. Daily thermal time linearly increases to the mean daily temperature above a base temperature (T_{base}) up to an optimum temperature (T_{opt}). Then, it linearly decreases until reaching the highest temperature (T_{high}) for crop development. The crop model calculates daily thermal time from hourly air temperature which is interpolated from the daily maximum and minimum temperatures. These daily thermal time values are then cumulated into the thermal time accumulation (in degree-day, °C d), which serves to determine the duration of each phenological stage (Bouman et al., 2001).

Other crop models, such as CERES (Ritchie et al., 1998) and APSIM (Meinke et al., 1997), are also conducted based on thermal time accumulation, primarily due to its ease of calculation.

2.3. Model simulation setup

Two 20-year model simulations were conducted at the Tonghua station. In Simulation One, the thermal time accumulations for four stages were set to the average 1985–1987 values, with each

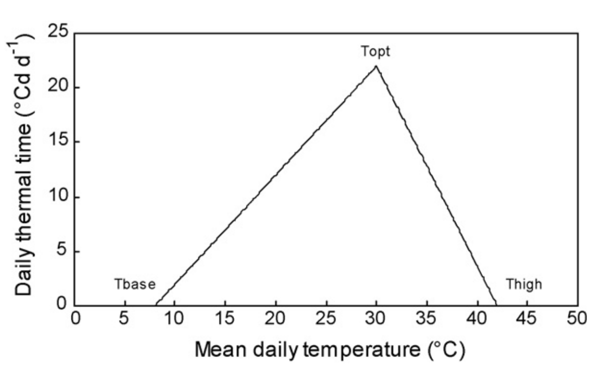


Fig. 1 – The response function of daily thermal time to temperature as used in ORYZA2000. Simulations with T_{base} = 8 °C, T_{opt} = 30 °C, and T_{high} = 42 °C.

simulation being representative of the phenological crop genetic coefficients for the Qiuguang rice variety. In Simulation Two, the calculated experiment-specific thermal time accumulation for each year was made to match the simulated phenological dates of the observations. The rest of the crop genetic coefficients were the same for each simulation. Following the climate-impact modeling studies (e.g. Matthews et al., 1995; Timsina and Humphreys, 2006; Zhu and Min, 1995), we used the default values of three cardinal temperatures for crop development (T_{base}, T_{opt}, and T_{high} as shown in Fig. 1), which are typically 8, 30, and 42 °C, respectively, according to Gao et al. (1992), Summerfield et al. (1992) and Yin (1996). In each simulation, the model was run under real management practices, taking into account potential water and nitrogen supplies, which include emergence dates, transplanting dates, local tillage density, and observed ambient CO_2 concentration for each year.

3. Results

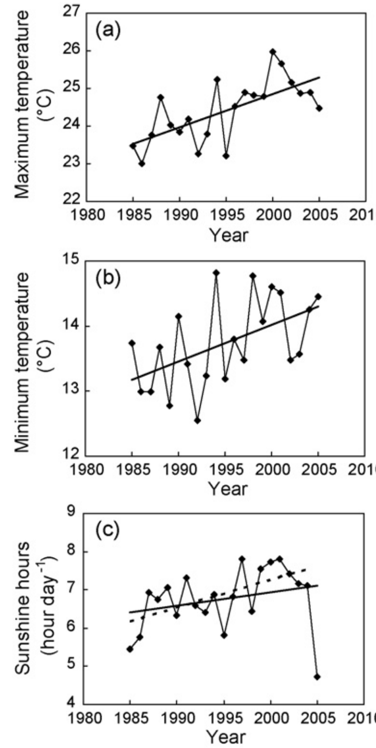
3.1. *Observed trends in meteorological conditions and phenological events*

Fig. 2 details the observed trends of averaged May–September (the primary growing season) maximum temperature, minimum temperature, and sunshine hours between 1985 and 2005 at the Tonghua station. It is evident that there are statistically significant increases in both the maximum ($P < 0.01$) and minimum temperatures ($P < 0.05$) as the growth rates for increases of 0.88 and 0.56 °C per decade in maximum and minimum temperatures occurred, respectively (Fig. 2a and b). The sunshine hours significantly rose between 1985 and 2004 at a rate of 0.72 h day^{-1} per decade ($P < 0.01$), followed by the lowest value recorded in 2005 (Fig. 2c). The general pattern of change in averaged May–September sunshine hours during the 20 years period, however, is positive. Fig. 3 gives the time trends of emergence, transplanting, flowering, and maturity dates over the two decades of observation. Rice phenological trends do not present as much change as those in meteorological conditions.

3.2. *Comparison between observed and simulated phenology and yields*

3.2.1. *Phenology simulation*

The differences between simulated and observed growing season lengths and flowering dates under Simulation One are shown in Fig. 4a and b. By considering the thermal time accumulation observed during 1985–1987 constant, the ORYZA2000 model consistently underestimates the length of growing seasons during the 1996–2005 study period. However, simulated growing season lengths are similar to the values observed from 1985 to 1996 (Fig. 4a). The average difference between 1985 and 1996 is only about 6 days, but it increases to 16 days during the 1996–2005 period. For flowering dates simulation, a similar pattern can also be observed (Fig. 4b). Under Simulation One, modeled growing season lengths shrink with time.



	Regression Equations	R^2	P-value
a	$y = 0.088x - 151.1$	0.44	<0.01
b	$y = 0.056x - 97.989$	0.27	<0.05
c(dashed line)	$y = 0.0716x - 135.99$	0.39	<0.01
c(solid line)	$y = 0.0343x - 61.676$	0.07	0.25

Fig. 2 – Time trend of average daily (a) maximum temperature, (b) minimum temperature and (c) sunshine hours over the main growing season (May–September) at the Tonghua station from 1985 to 2005. In (c), the dashed line is regression line for data during 1985–2004; the solid line is for that during 1985–2005; regression equations, coefficients of determination (R^2) and P-values are shown in the accompanying table.

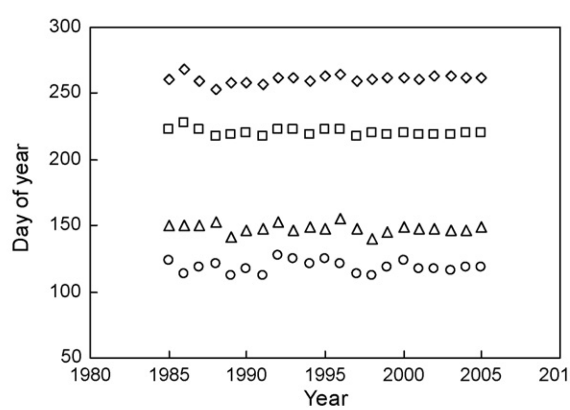


Fig. 3 – Time trend of emergency dates (○), transplanting dates (△), flowering dates (□) and maturity dates (◇) from 1985 to 2005 at the Tonghua station.

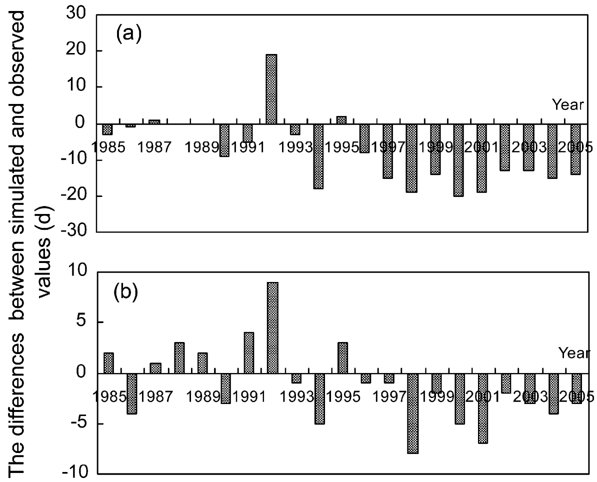


Fig. 4 – Time trend of differences (simulated − observed) between simulated and (a) observed growing season length and (b) flowering date under Simulation One.

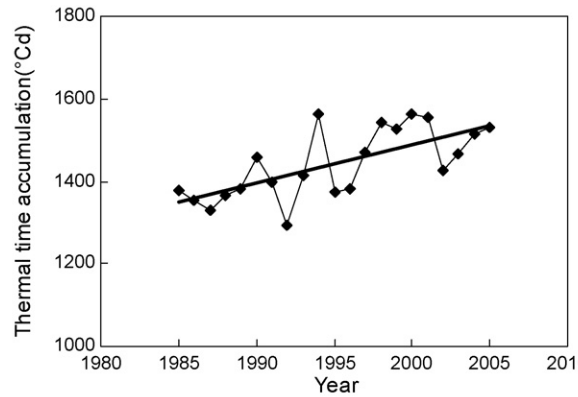


Fig. 6 – Time trend of thermal time accumulation from transplanting to maturity at the Tonghua station. Thermal time accumulations were calculated in the same way of ORYZA2000. Linear regression equation is $y = 9.3549x - 17221$ ($R^2 = 0.48$, $P < 0.01$).

3.2.2. *Yield simulation*

Fig. 5a compares simulated yields with measured yields for the whole dataset at the Tonghua station using calculated experiment-specific thermal time accumulation values for each year (Simulation Two). Based on the graphical comparisons, the simulation of yields is comparably accurate. The normalized root mean square errors ($RMSE_n$) for this simulation are approximately 19%. This is only slightly higher than those of lowland rice reported in the other literature, where the reported $RMSE_n$ generally varied within the range of 11–16% (Belder et al., 2007; Boling et al., 2007).

Fig. 5b illustrates the time trend of change in modeled yields under the two model simulations, together with the equivalent observed results. Simulation One, using the averaged thermal time accumulation from 1985 to 1987, predicts that yields would decline in spite of the beneficial physiological effects of an increase in CO_2 concentration. However, Simulation Two, using calculated experiment-specific thermal time accumulation, simulates a similar pattern in yield to the actual observed results.

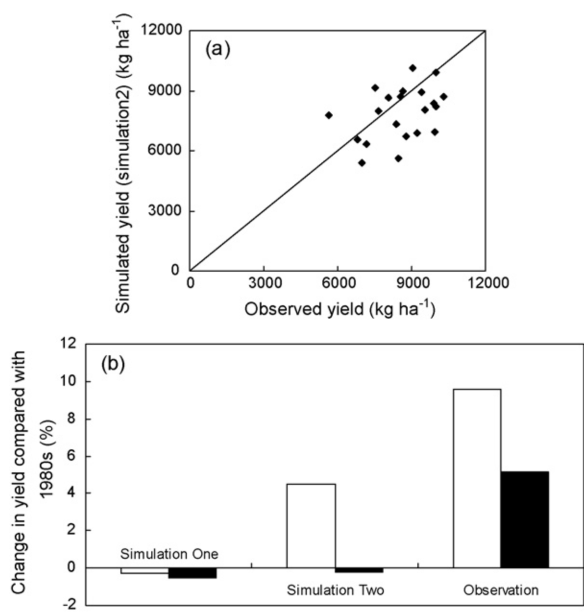


Fig. 5 – (a) Simulated versus measured yields (◆) for 1985–2005 at the Tonghua station (dashed line is the 1:1 line) under Simulation Two; (b) the change in the average yield (%) in the 1990s (□) and 2000s (■) than 1980s.

3.3. *Time trend of thermal time accumulation*

Fig. 6 shows the time trend of thermal time accumulation from transplanting dates to physiological maturity dates. There is an increase in thermal time accumulation at the Tonghua station during 1985–2005. An averaged thermal time accumulation of approximately 1360 °C d was enough for completing crop development during the 1985–1987 time period, while more thermal time accumulation (approximately 1500 °C d) was needed between 2003 and 2005. Although gradual, the increase in thermal time accumulation is statistically significant ($P < 0.01$), taking place at a rate around 9.4 °C d per year over the course of the entire time period.

3.4. *Sensitivity experiments*

Sensitivity experiments were conducted to examine the effects of the three cardinal temperature parameters (T_{base}, T_{opt}, and T_{high}, as shown in Fig. 1) regarding thermal time accumulation tendencies during the 20-year period. Sensitivity experiments were created by combining step changes in the three cardinal temperature parameters. Five levels (−10%, −5%, 0, 5%, 10%) in the three parameters were set (Table 1), generating a total of 125 combinations. The response variable analyzed was the rate of change in thermal time accumulation from 1985 to 2005 (the slope of a linear regression in Fig. 6). The results of the sensitivity experiments are summarized in Fig. 7. T_{opt} is the most sensitive parameter among the three cardinal temperatures; however, it should also be noted that the rates of change in thermal time accumulation remain positive, and show a variability of between 7 and 10 °C d per year.

Table 1 – Changes in the base temperature, optimum temperature and highest temperature for rice development in sensitivity experiments

Parameter	Description	−10%	−5%	0	5%	10%
T_{base}	Base temperature (°C)	7.2	7.6	8.0	8.4	8.8
T_{opt}	Optimum temperature (°C)	27.0	28.5	30.0	31.5	33.0
T_{high}	Highest temperature (°C)	37.8	39.9	42.0	44.1	46.2

4. Discussion

As shown in Simulation One (Fig. 4a and b), the modeled growing season lengths and flowering dates match very well with the observed values over the course of a short study period, exhibiting a difference of only about 6 days. The results are comparable in terms of accuracy with previous studies, which have generally reported a difference of approximately 5–8 days for flowering dates, using four phenology-prediction models for lowland rice (Yin et al., 1997); a difference with an average of 5.5 days for flowering dates, when using the CERES-Rice model (Yao et al., 2007); and a difference of 4–5 days for maturity dates, when using the CERES-Rice model (Saseendran et al., 1998; Timsina et al., 1998). This suggests that the ORYZA2000 model is able to produce no less accurate phenological simulations than other crop models when the study period is short.

However, for the longer study periods, the modeled growing season lengths and flowering dates under Simulation One were constantly underestimated by an average value of 16 days in the period of 1996–2005. The majority of modeling studies have concluded that growing season lengths shrink due to the more rapid accumulation of thermal time under higher temperatures (Kwak and Lee, 2006; Xiong et al., 2007; Yao et al., 2007). Similarly, Simulation One, using the constant thermal time accumulation, also modeled a decline in growing season length with time. This was, however, not consistent with the observed pattern. Thus, this indicates that even though a crop model simulation based on the constant thermal time accumulation is able to reproduce relatively accurate phenological dates during a short study period, large deviations in phenology simulations still occur over the course of a long-term climate series.

Contrary to the notion assumed in previous studies, thermal time accumulation is not constant, and in fact rose with time at the Tonghua station (Fig. 6). Our sensitivity experiments also support this point (Fig. 7). We found that even if the three cardinal temperatures varied within the range of ±10%, the time trend of thermal time accumulation would still have been positive over the 20-year period. Yin et al. (1996) measured the optimum temperature of 24 indica and japonica rice varieties in various Asian countries, including the Philippines, China, Japan and Korea. Their observations showed that the optimum temperature for the development of these rice varieties varies over the range of 28–30 °C, a detail which is not excluded in our sensitivity experiments. Therefore, these results indicate that assuming thermal time accumulation to be a constant is not reasonable, as this is the primary reason for the underestimation of phenology in long-term simulations at the Tonghua station.

As for yield simulations, consistent with the conclusions of previous modeling studies, Simulation One, which was based on constant thermal time accumulation, predicted a decline in rice yields due to shorter modeled growing seasons (Fig. 5b). However, Simulation Two, using the observed phenological dates, suggested a similar pattern in rice yields for the observed values from 1985 to 2005. This part of the analysis

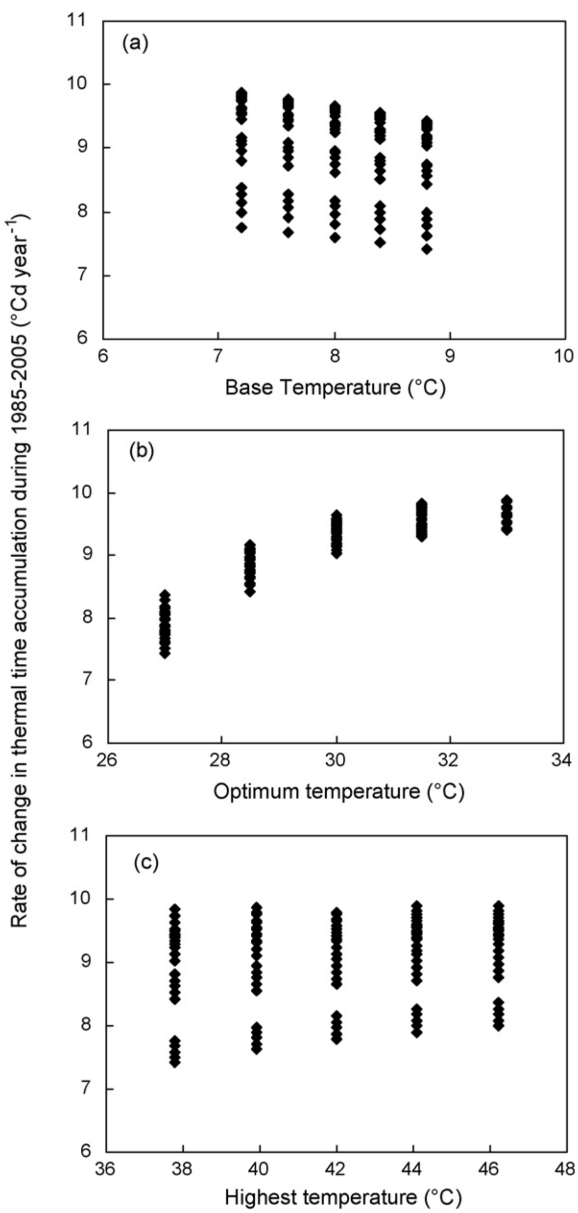


Fig. 7 – Sensitivity of the rate of thermal time accumulation (the slope of a linear regression in Fig. 6) from 1985 to 2005 at the Tonghua station to changes in (a) base temperature (T_{base}), (b) optimum temperature (T_{opt}) and (c) highest temperature (T_{high}) for rice development.

suggests that the underestimation of phenology simulations at the Tonghua station causes the misleading yields modeling. Improvements in yield simulations may be expected if future models can simulate a more accurate phenological trend due to climate change.

5. Conclusions

The assumption of constant thermal time accumulation is very important in the modeling studies relevant to climate change impacts on agriculture. Our long-term observed data clearly demonstrates that assuming a constant thermal time accumulation is not always suitable for studies of climate change impacts on agriculture. Using thermal time accumulation to accurately model climate change is a field that still needs future study.

However, we caution against extrapolating the increasing trends in thermal time accumulation observed at the Tonghua station to other places. Whether the similar increases in thermal time accumulation can be seen in other regions remains to be determined due to the lack of long-term single rice variety data at other places. More research must still be completed to create accurate thermal time accumulation simulations that are suitable for the use in climate and yield production studies.

Acknowledgements

We appreciate Dr. B.A.M. Bouman and two anonymous reviewers for their valuable comments, and also wish to thank the CMA for providing crop and meteorological data. Finally, we also thank Mr. James R. Wright and Dr. John H.C. Gash who helped improve the clarity of this manuscript.

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