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ORIGINAL PAPER

Potential agro-thermal resources dynamic for double-season rice cultivation across China under greenhouse gas emission scenarios

Lei Zhang[1,2] · Sen Li[1] · Fangying Tan[1] · Anhong Guo[1] · Zhiguo Huo[3]

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Abstract
Maintaining the current levels of rice production in the face of future climate changes is an enormous challenge for agriculture. The use of high-resolution projections derived from statistical downscaled global climate models and dynamic downscaled regional climate models can assist in maximizing yield for double-season rice. The thermal indices of secure sowing date (SSd), secure maturation date (SMd), potential growing season (PGS), and growing accumulated temperature ≥ 10 °C (GAT10) were explored in future sub-periods under two greenhouse gas emission scenarios (RCP4.5 and RCP8.5). The trends predicted were advancements in SSd and delays in SMd across major areas of China. A comparison of RCP4.5 and RCP8.5 scenarios indicated that SSd advanced by 1–39 and 1–49 days in 2081–2095 relative to the baseline period of 2001–2015 while SMd was postponed by 11–60 and 11–70 days, respectively. Under RCP4.5, PGS was prolonged by 1–50, 1–60, 21–90, and 31–90 days in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 relative to baseline, respectively. Within these same periods using RCP8.5, PGS advanced 1–50, 31–90, 41–90, and 51–90 days, respectively. A comparison of the relative contributions of SSd and SMd to PGS indicated that higher levels of SMd contributed prominently in the PGS increase. In addition, as the climate continued to warm, GAT10 levels would likely continue in an upward trend and were predicted for 2081–2095 to reach 500–2500 °C·day under RCP4.5 and 1500–3000 °C·day under RCP8.5. Regionally, earlier SSd, later SMd, longer PGS, and larger GAT10 values were projected for southern regions in Guangdong, Guangxi, and Hainan. This type of information is also a potential resource available to farmers to make informed decisions on timely cultivation adjustments and variety selections for specific climatological areas.

1 Introduction

China is the largest producer and consumer of rice in the world accounting for 32% of global production supplied to 65% of its population (FAO 2020). However, production is threatened because regional warming is undergoing a magnitude larger than the global level and this is expected to have a significant negative impact on rice yield (IPCC 2013; Soora et al. 2013). Additionally, expected future population increases will require an increase in production of staples, such as rice, and agricultural adaptive strategies are urgently needed that ultimately will rely on modeling the future climate (Rippke et al. 2016).

Climate model projections are commonly based on greenhouse gas emission (GHG) scenarios. The two prevalent climate model types are global climate model (GCM) and regional climate model (RCM). These have been applied to explore the impacts of climate change on rice production and have their primary focus on planting distribution, disasters, and yield projections (Teixeira et al. 2013; Wang et al. 2014; Zhang et al. 2017; Mall et al. 2018; Zhang et al. 2018a). These models are derived from mitigation scenarios aimed to limit the increase of global mean temperature to 2 °C and derived from Representative Concentration Pathways (RCP) that are greenhouse gas concentration trajectories. For instance, a recent GCM predicted that areas suitable for rice cultivation would shift in RCP2.6 and RCP8.5 scenarios (Zhang et al. 2017). The likelihood of these predicted outcomes is incorporated into other models including the Coupled Model Intercomparison Project Phase 5 (CMIP5)

✉ Lei Zhang
lei_z2011@163.com

1 National Meteorological Center, Beijing 100081, China

2 Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences, Beijing 100081, China

3 Chinese Academy of Meteorological Sciences, Beijing 100081, China

that is an ensemble of 20 GCMs based on RCP8.5 scenarios. In this ensemble, rice will be exposed to greater levels of heat stress at increasing magnitudes over a wide geographic range (Zhang et al. 2018a).

These climatic alterations will separately lead to a reduction in rice yield but can be offset by CO_2 fertilization strategies associated with future scenarios (Wang et al. 2014; Yu et al. 2014; Lv et al. 2018; Kontgis et al. 2019). In the face of these immense challenges, the use of available agro-climate resources is essential for the successful implementation of adaptation strategies since effective CO_2 fertilization methods are in their infancy (Li et al. 2018; Zhao and Yang 2018). Overall, the length of the growing season will increase and crucial phenology periods that are linked to rice yield will be shortened with the current rice varieties (Ding et al. 2017; Lv et al. 2018; Zhang et al. 2018a). New rice varieties adapted to these changes can markedly promote rice yield, and yield will be likely to increase by 0.44 t/ha in the middle years of the twenty-first century (Bai et al. 2016; Gao et al. 2019; Yu et al. 2014). Thus, selection of plant varieties and planting decisions will be directly associated with increased yield.

The accuracy and representation of climate change impacts on rice cropping at regional or local scales generally depend on the reliability and resolution of projections. Compared to raw GCM, statistical downscaling and dynamic downscaling (i.e., RCM) can result in more reliable projections that benefit from a higher level of resolution (Rummukainen 2010; Liang et al. 2018). Nonetheless, few attempts have been made to project climate change impacts on rice production (Ma et al. 2013; Li et al. 2018; Mall et al. 2018). The most widely applied calculations utilized single use statistical or dynamic downscaling, but these approaches have not been coupled whereas analyses based on both could generate high-resolution models. In the current work, we explored how much will future climate change the potential growing period for double-season rice across China relative to the current level? To what extent can farmers change the variety to use potential availability from future climate resource?

2 Material and methods

2.1 Study area and data source

The planting areas for double-season rice were in southern Jiangsu, southern Anhui, southeastern Hubei, Zhejiang, Jiangxi, Hunan, Fujian, Guangdong, Guangxi, and Hainan (Fig. 1). Within these regions, GCM and RCM temperatures were not always consistent with observations and it was thus necessary to implement bias correction for reproducing temperatures. Previously, 20 statistical downscaled GCMs and dynamic downscaled RCM were validated and top 5 models which performed well were utilized in each climatic region (Zhang et al. 2020). Specifically, our study area covered two climatic regions: (1) South China including Fujian, Guangdong, Guangxi, and Hainan and (2) south of the Yangtze River including southern Jiangsu, southern Anhui, southeastern Hubei, Zhejiang, Jiangxi, and Hunan. The top five models for reproducing mean temperature (Tm) were selected separately for (1) South China (statistical downscaled IPSL-CM5A-LR, ACCESS1-0, HadGEM2-ES, and BNU-ESM, as well as bias-corrected PRECIS) and (2) south of the Yangtze River (statistical downscaled IPSL-CM5A-LR, IPSL-CM5A-MR, CNRM-CM5, CCSM4, and CSIRO-Mk3-6-0). The datasets provided from these models included daily Tm at a resolution of 0.25° × 0.25° for the historical period 1961–2005 and future period 2006–2100 under RCP4.5 and RCP8.5 scenarios.

2.2 Assessing index of agro-climatic resources

The appropriate sowing and maturation dates were necessary to optimize the rice growing period and were typically corresponding to the beginning date of Tm ≥ 12 °C and ending date of Tm ≥ 15 °C, respectively. These were taken as the sowing and maturation time for double-season rice cropping and were calculated using a 5-day moving average method in order to eliminate the effects of random fluctuation in Tm (Yan et al. 2011; Dai et al. 2015; Ye et al. 2015). The secure sowing date (SSd) was determined to be the date when there were no subsequent continuous 3 days with Tm < 12 °C. Similarly, the secure maturation date (SMd) was the day when there were no subsequent continuous 3 days experiencing Tm < 15 °C. The period between SSd and SMd was named the potential growing season (PGS).

Growing accumulated temperature ≥ 10 °C (GAT10) was defined as the sum of the Tm during a period in which Tm was ≥ 10 °C each day and was the widely applied standard used to determine agricultural temperature zones, crop varieties, and crop patterns (Hou et al. 2014; Dai et al. 2015; Li et al. 2018). Rice varieties were distinguished as short-duration, medium-duration, and long-duration cultivars classified using GAT10, and this was used as an index for adjusting rice variety. The differences in the GAT10 trends during the years 2001–2015 were not significant enough to affect the growing period for rice at most agro-meteorological experiment stations (Fig. S1 and Fig. S2). Therefore, this period was used as baseline for the current climate and rice growing stages. The actual sowing date (ASd), actual maturation date (AMd), actual growing season (AGS), and actual GAT10 in this study were calculated by daily observed temperatures from 500 meteorological stations within the region and were obtained from China Meteorological Data Sharing Service System (Fig. 1). These data were strictly quality-controlled to keep internal long-term consistency and homogeneity over 2001–2015. ASd and

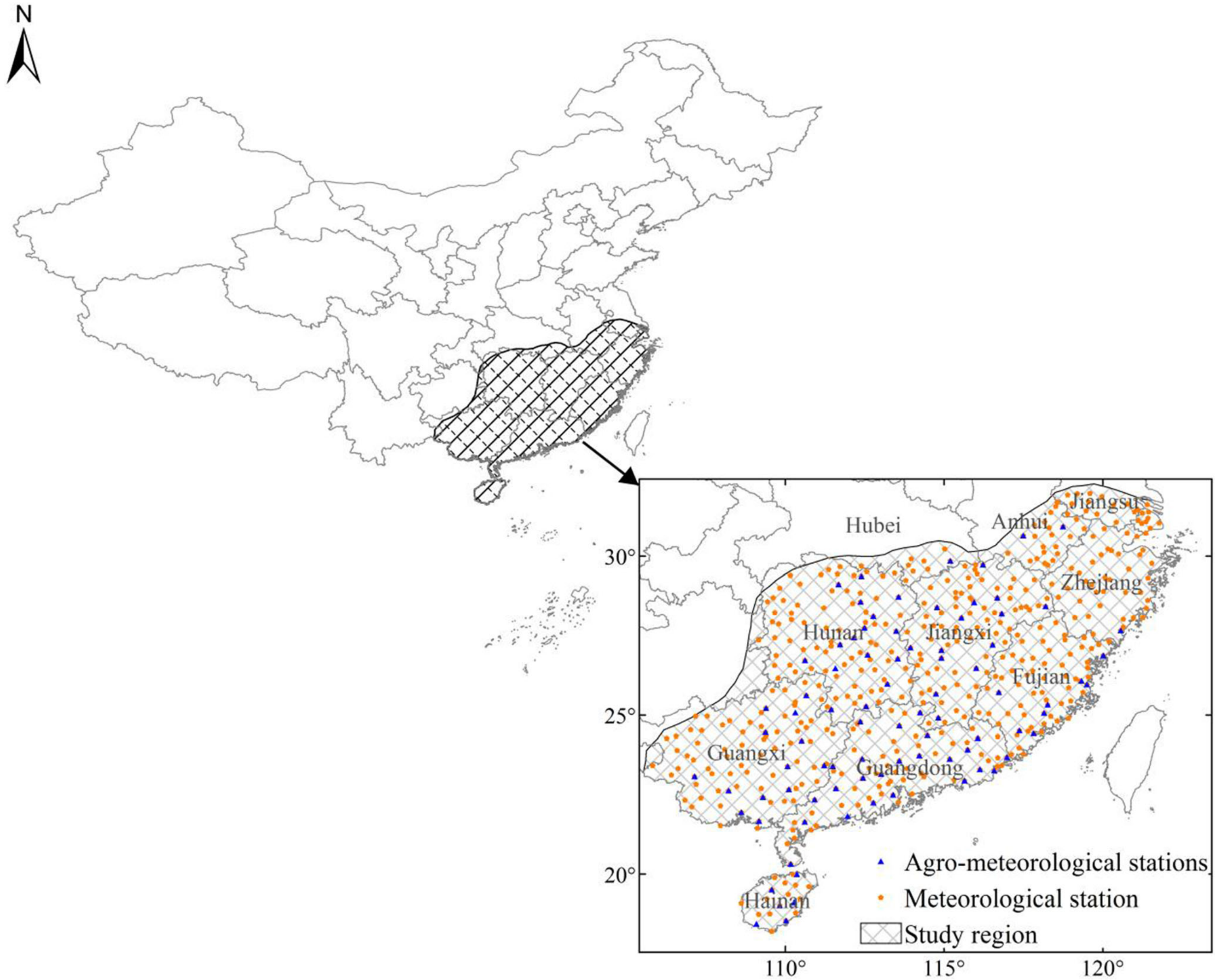

Fig. 1 Location of study region

AMd at meteorological stations were substituted by ASd and AMd at its nearest agro-meteorological experiment station.

The future periods were then divided into four sub-periods: 2021–2035, 2041–2055, 2061–2075, and 2081–2095. Future SSd, SMd, PGS, and GAT10 were explored under RCP4.5 and RCP8.5 scenarios, and uncertainty was minimized by using the ensemble of the top five models for each climatic region. The dates used in this study were indicated using the day of year calendar (DOY).

3 Results

3.1 Potential change of sowing date and maturation date

The data for 2001–2015 indicated that ASd increased from south to north within the range DOY 91–102 in southern Jiangsu and Anhui, northern Zhejiang, and Hunan. Relative to this baseline, the predicted SSd in 2021–2035 under RCP4.5 was 1–29 days earlier in most parts except for southwestern Hunan, western Jiangxi, central Fujian, and southeastern Zhejiang in which the delay was 1–10 days. The SSd change predicted for 2041–2055 was 1–10 days later in Hunan, central-western Jiangxi, southern Zhejiang, western Fujian, northern Guangxi, and northwestern Guangdong but 10–39 days earlier in southern parts. For 2061–2075 and 2081–2095, SSd was 1–49 days earlier with the exception of an extension of 1–9 days in some specific regions. The SSd advances in 2021–2035 in comparison with baseline were similar between RCP4.5 and RCP8.5 scenarios. The advancement of SSd was more obvious and increased up to 10–49 days in most parts of the study area and was > 50 days in southern Guangdong and southern Guangxi for 2081–2095 (Fig. 2).

The observed AMd for the baseline revealed a decrement from south to north with the highest value of DOY 311–323 in eastern Zhejiang, southeastern Guangdong, and southern

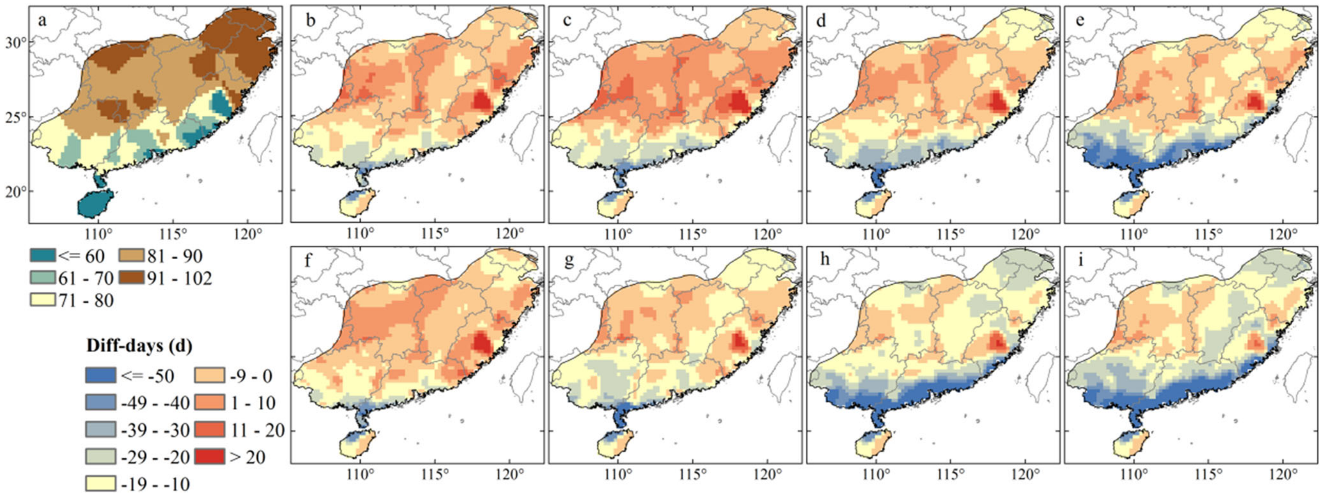

Fig. 2 Actual sowing date in 2001–2015 and future change of secure sowing date relative to 2001–2015 (**a** the value in 2001–2015; **b**–**e** the value in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCP4.5, respectively; **f**–**i** the value in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCPP8.5, respectively)

Guangxi, and lowest before DOY 270 in eastern Hainan. In contrast, SMd in 2021–2035 and 2041–2055 was postponed by 1–40 days in most parts and 41–70 days in southern Guangdong with the exception of some eastern parts of Zhejiang. In 2061–2075 under RCP4.5 relative to baseline, SMd was 31–70 days later in Guangdong, Guangxi, and Hainan and 11–30 days later in other parts. An increasing delay of SMd was calculated for 2081–2095 with a general value of 21–70 days. Under RCP8.5, SMd in 2061–2075 was 21–70 days later than baseline and possessed a larger magnitude than in 2081–2095 under RCP4.5. For 2081–2095 under RCP8.5, SMd was significantly delayed by 31–70 days. Generally, SMd was postponed to a later period as the warming climate and a longer delay were predicted under RCP8.5 (Fig. 3).

3.2 Potential change of growing season

Variations in sowing and maturation dates indicated that the length of the growing season varied with time. AGS increased from 194–210 days in northern regions to 256–290 days in southern regions over the baseline period. In 2021–2035 and 2041–2055 under RCP4.5, PGS was prolonged by 1–30 days in northern parts (southern Jiangsu, southern Anhui, south-eastern Hubei, western Zhejiang, Jiangxi, central-eastern Hunan) and 31–90 days in southern parts (southern Fujian, Guangdong, Guangxi, and Hainan). The PGS continued to increase by 21–90 and 31–90 days for 2061–2075 and 2081–2095, respectively. In terms of RCP8.5, PGS extensions were similar in 2021–2035 under RCP4.5, and were extended 31–90, 41–90, and 51–90 days in 2041–2055, 2061–2075,

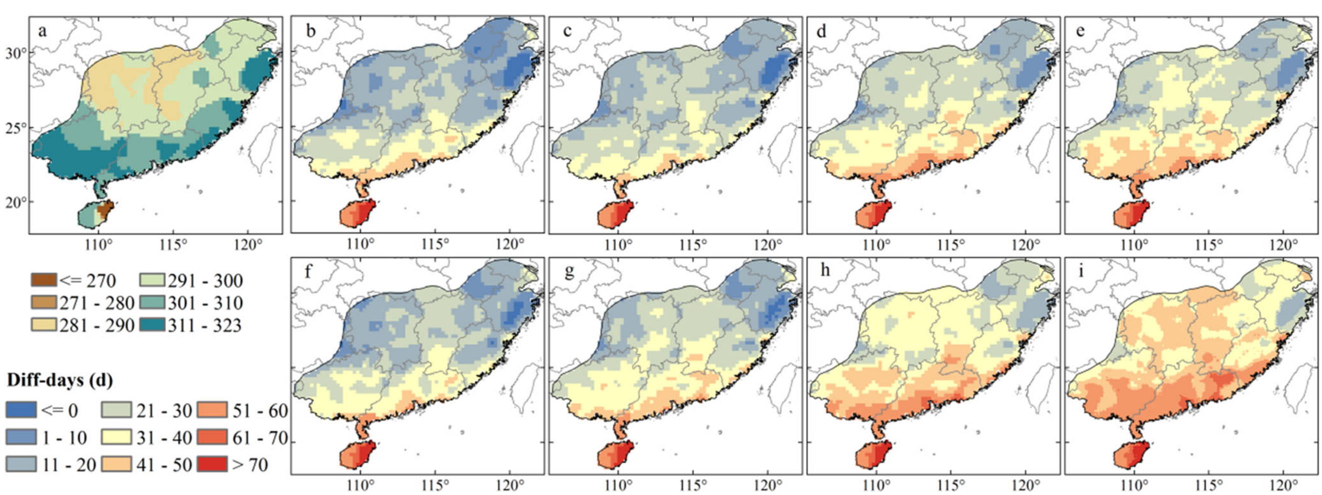

Fig. 3 Actual maturing date in 2001–2015 and future change of secure maturing date relative to 2001–2015 (**a**–**i** are the same as Fig. 2)

and 2081–2095, respectively. Overall, longer PGS was predicted for most areas using RCP4.5 and RCP8.5 in 2021–2035, and more obvious increments were found for subsequent periods under RCP8.5 (Fig. 4).

SMd differences and SSd changes relative to baseline were additionally calculated to determine their contribution to the change in PGS. The positive values indicated that the prolongation of SMd was larger than the advancement of SSd and this was consistently 1–30 days for in most areas, 31–50 days in central Fujian and eastern Guangdong, and > 50 days in Hainan in 2021–2035 under RCP4.5 and RCP8.5. In 2041–2055, the difference reached 21–40 days in central parts under RCP4.5, larger than RCP8.5. In 2061–2075, a difference of 11–50 days was calculated for the major areas and was > 50 days in Hainan under RCP4.5 and RCP8.5. However, the differences for southern Guangdong and southern Guangxi were negative under RCP8.5 and opposite to that under RCP4.5. In 2081–2095, the difference was 11–50 days under RCP4.5 but was obviously larger for central-western Hunan and western Jiangxi under RCP8.5. Comparatively, southern Guangdong and southern Guangxi values were negative in 2081–2095 relative to 2061–2075, and overall, the difference was negative in southern Jiangsu, southern Anhui, and central-eastern Zhejiang. These calculations corroborated that the larger PGS increments were primarily attributed to a prolonged SMd (Fig. 5).

3.3 Potential change of GAT10

The potential changes for GAT10 were explored for the current and future periods over our study region. GAT10 in 2001–2015 ranged from < 5000 °C·day in some northern areas (southern Jiangsu, southern Anhui, southeastern Hubei, western Zhejiang, northwestern Jiangxi, and Hunan) to 7000–7500 °C·day in some southern localities (southeastern Guangdong, western Hainan). Following warming, GAT10 generally increased spatially under RCP4.5 and RCP8.5 scenarios. GAT10 extended to 5000–8500, 5500–9000, 5500–9500, and 6000–10,000 °C·day in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCP4.5. These values were 5000–9000, 6000–9500, 6000–10,000, and 6500–10,000 °C·day in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCP8.5, respectively. Comparisons for the RCP indicated that GAT10 differences were similar for the two models in 2021–2035 but predicted increases for RCP8.5 were greater than that for RCP4.5 in future periods (Fig. 6).

In contrast with baseline, an increment of 1–1000 °C·day in GAT10 was demonstrated for most of the study region but also 1500–2500 °C·day in southern Guangdong and Hainan in 2021–2035 under RCP4.5 and in 2041–2055 under RCP4.5 and 2021–2035 under RCP8.5. GAT10 increased in the range of 500–1500 °C·day over the major parts of the study area and 1500–3000 °C·day in southern Guangdong, southern Guangxi, and Hainan in 2061–2075 under RCP4.5, 2081–2095 under RCP4.5, and 2041–2055 under RCP8.5. There was a general increase of 1000–2000 °C·day for GAT10 in the majority of the study regions and 2000–3000 °C·day in southern Guangdong, southern Guangxi, and Hainan in 2061–2075 under RCP8.5. Furthermore, a significant incremental increase in GAT10 continued over 2081–2095 under RCP8.5. This demonstrated a 1500–3000 °C·day increment in most parts and over 3000 °C·day in southern Guangdong, southern Guangxi, and Hainan (Fig. 7).

4 Discussion

The results from our climate scenarios indicated that relative to recent climatic conditions, future climate change would have a definite influence on agricultural production and management systems. We assessed potential of rice exposure to

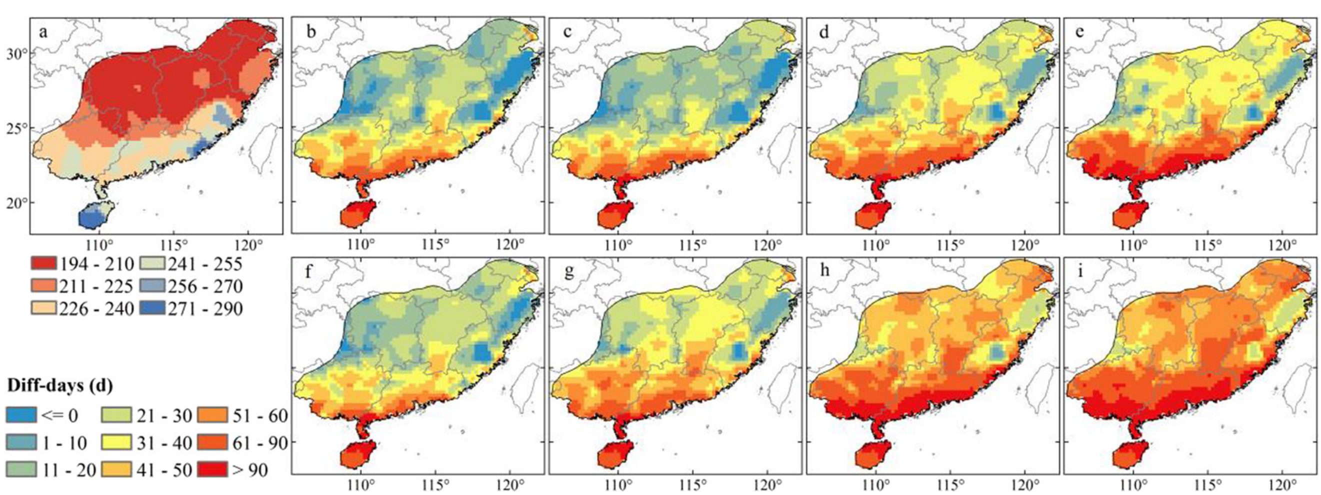

Fig. 4 Actual growing season in 2001–2015 and future change of potential growing season relative to 2001-2015 (**a**–**i** are the same as Fig. 2)

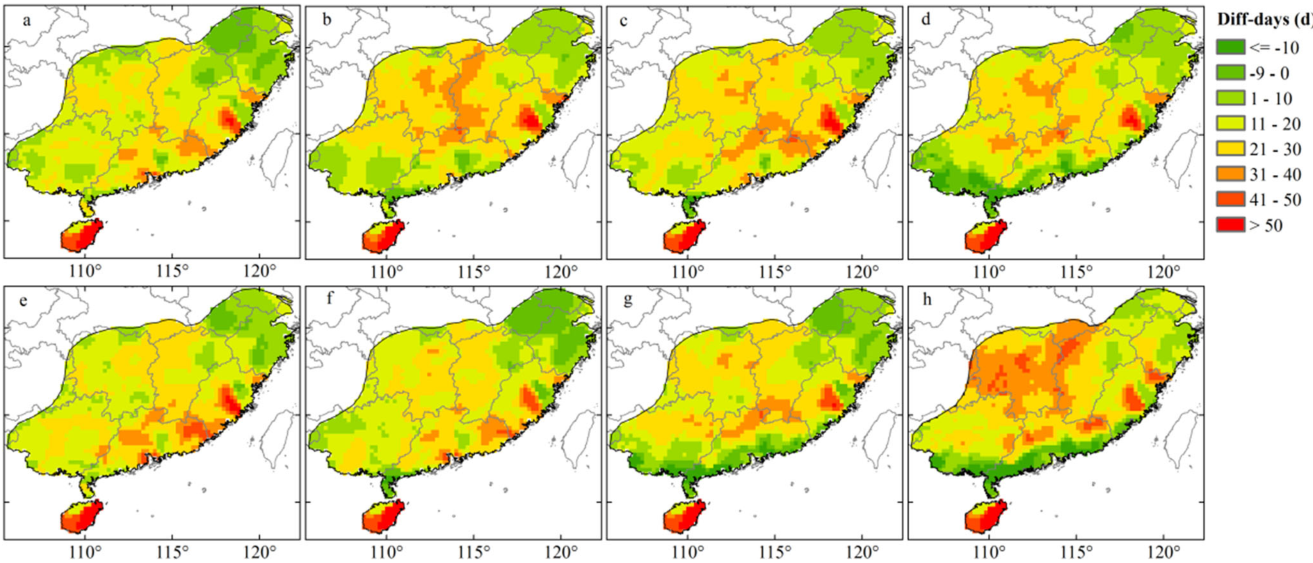

Fig. 5 The difference of change of secure maturing date and sowing date in the future periods (**a**–**d** the value in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCP4.5, respectively; **e**–**h** the value in 2021–2035, 2041–2055, 2061–2075, and 2081–2095 under RCPP8.5, respectively)

climatic alterations with special emphasis on temperature for the study regions for double-season planting. Bias correction was frequently applied to match outputs from climate models to observed data before using projections to assess climate change impact (Crimp et al. 2018; Li et al. 2018). These manipulations resulted in minimal deviations relative to the observed values (Mall et al. 2018). We therefore applied the temperatures simulated from the top 5 well-performed models and the observations across our two climatic study regions. The ensemble of optimal climate models was then used for assessing climate change impacts.

During the baseline period (2001–2015), the growing season for double-season rice fluctuated within a limited value range for the majority of the study areas (Fig. S1 and Fig. S2). This indicated that the mean phenology throughout the period was stable and this had been previously calculated (Zhang et al. 2018b). Under future GHG scenarios, SSd was advanced and SMd was postponed within a discrete range across the study areas and led to a longer PGS. Previous studies had calculated similar results for growing periods in some area of our study regions (Ding et al. 2017; Wang et al. 2017; Lv et al. 2018). The duration of growing period for early rice in the middle and lower reaches of the Yangtze River was projected to continually shorten from 2020 to 2080 under RCP4.5 and RCP8.5 (Ding et al. 2017). Additionally, for a specific phenological period such as grain-filling, this value was also shortened by 2–7 days and 10–19 days in the future from 2030 to 2070 for early and late rice, respectively (Lv et al. 2018). These findings indicated a shortening of growing period under ongoing warming scenarios and that warming would accelerate phenology development for rice. This same growing period could be suitable for another rice variety that

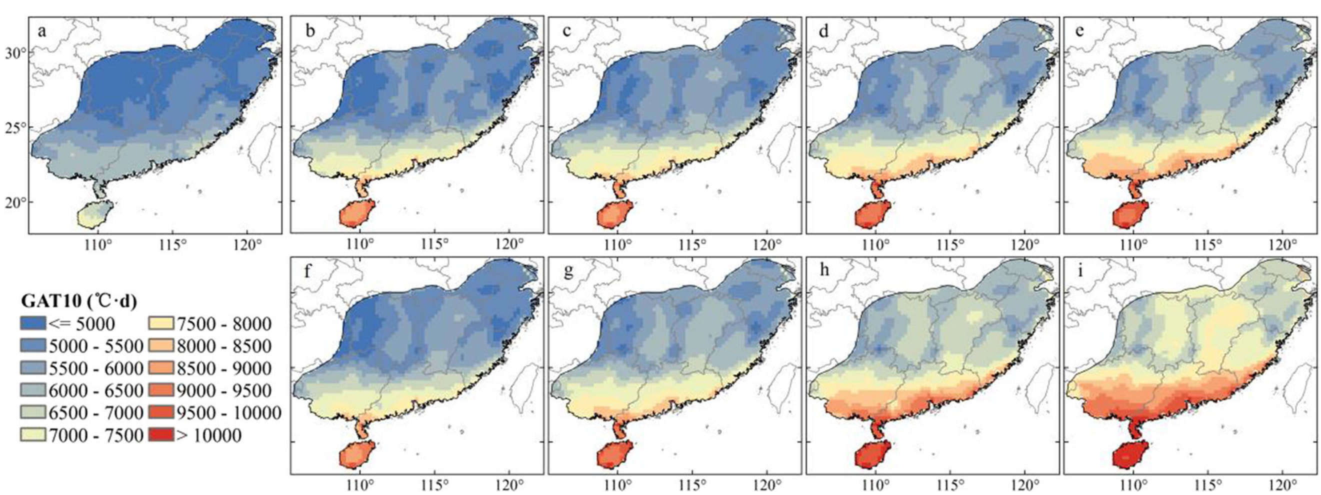

Fig. 6 GAT10 in different periods (**a**–**i** are the same as Fig. 2)

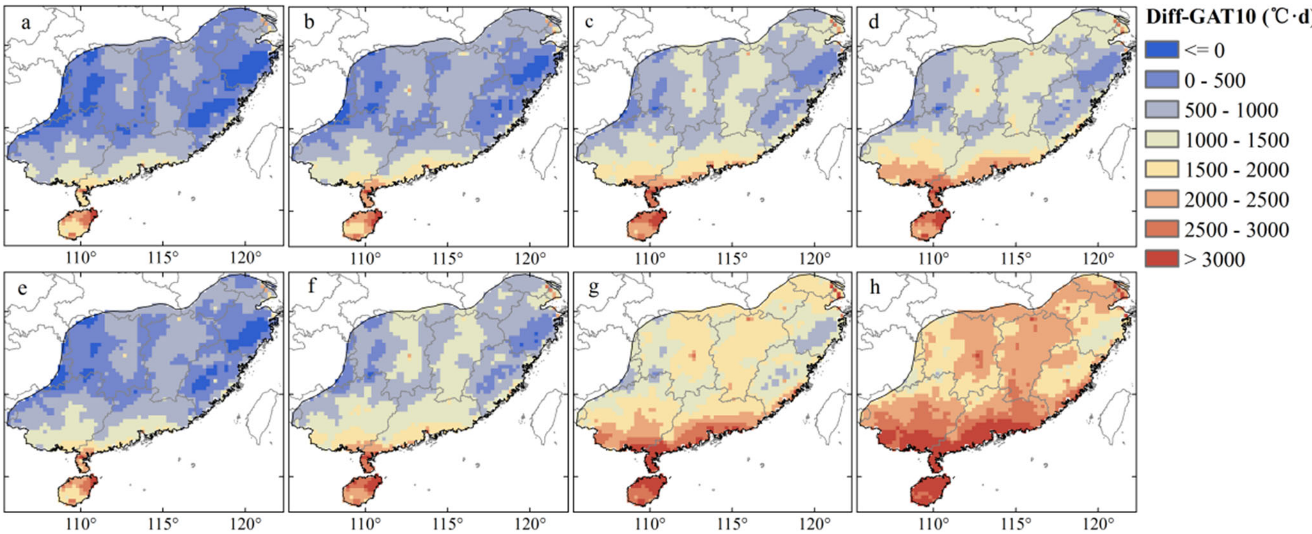

Fig. 7 Change of GAT10 relative to 2001–2015 (**a**–**h** are the same as Fig. 5)

possessed a higher magnitude accumulated temperature phenotype and was consistent with our GAT10 results (Yu et al. 2014). The predictions of sowing and maturation dates indicated a longer PGS emerged for double-season rice and had been previously defined (Wang et al. 2017).

Our future climate scenarios concentrated on the temperature change aspect of climate alteration. Generally, rice yield forced by future climate change would be reduced if the plant variety remained constant in future periods (Cao et al. 2014; Yu et al. 2014). The losses in rice yield singly associated with climate change could be offset with CO_2 fertilization (Lv et al. 2018; Kontgis et al. 2019). However, this kind of promotion in rice yield was not an advisable measure in response to climate change in the absence of initiative activities. The best and most effective use of agro-climate resources would therefore employ currently available resources. In particular, the potential advancement of sowing date and delay of maturation date could be offset by adjusting the farming dates and this had been successfully applied on a practical scale (Cao et al. 2014; Lv et al. 2018). The later maturation dates also led to increased grain weights. Moreover, the use of specifically adapted rice varieties could also be used to cope with climate change. Cultivars with longer duration growing periods was one common practice to mitigate climate change impacts and achieve higher yield. Yield reductions could be prevented by using varieties that required more thermal time (Olesen et al. 2011). Relative to old varieties, these newer varieties markedly increased rice yield with a increment of 26.4% from 1981 to 2009 and became more adaptive to the warmer climate (Bai et al. 2016). To extract contributions of yield change, about 21.7% could be attributed to a change in variety in the 2000s relative to the 1980s (Liu et al. 2013). Future climatic conditions using these changes that involved an unchanged growing season were predicted to increase yield by 3.2% (Yu et al. 2014). Specific regional adaptations such as varieties with longer growing seasons and tolerant of more thermal time would be used in southern rather than northern regions. The current double-season cultivar in some southern regions could also be used as a triple-season cultivar to make the best use of the longer PGS (Kontgis et al. 2019).

As a matter of practice, it was difficult to use the entire potential growing season and available resources such as varietal planting. One reason was that the date of rice growing was traditionally decided according to previous experience or traditional knowledge and governmental policies apart from climatic conditions (Ye et al. 2015). There was a change from double-season to single-season rice planting due to rising farming costs and labor shortages. The suggestions provided in this work were intended to illustrate resources available for rice cultivation excluding these non-climatic factors. The use of the entire growing season would be adverse to yield due to heat stress which was particularly extreme for the case of Zhejiang, central-northern Fujian, and eastern Jiangxi (Zhang et al. 2018a; Zhang et al. 2018b). These extremes could be avoided by harvesting earlier for early rice and planting later for late rice minimizing as a longer PGS would be available. However, the appropriate times for these practices have yet to be developed on a practical scale.

In this study, RCP4.5 and RCP8.5 scenarios were selected to reveal the potential change of agro-thermal resources dynamic for double-season rice under the medium and high GHG emission level, as the RCP scenarios were proposed in CMIP5 and highlighted in the fifth IPCC report. The Paris Agreement sets a temperature goal that was holding the increase in the global mean temperature below 2 °C above pre-industrial levels and pursuing efforts to limit it to 1.5 °C. Previous results concluded that less impact of climate change on human system would be detected in 1.5 °C target relative to

2 °C target, derived from the analysis on CMIP5 RCP scenarios (Zhou et al. 2018; Zhang et al. 2018c). However, the RCP scenarios were not designed for the 2.0 °C or 1.5 °C target; to some extent, they would be not reasonable enough. More proper assumptions should be proposed to project future climate change as the emission scenarios would not be sure in the future. Thus, shared Socio-economic Path (SSP) scenarios were proposed in CMIP6, including SSPa-b, SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-3.4, SSP4-6.0, SSP5-3.4-OS, and SSP5-8.5. The scenarios could support specific analysis for the 1.5 °C target (SSPa-b) or 2.0 °C target (SSP1-2.6), update of RCP scenarios, and more new experiments design in the consideration of more uncertainty in the future. So, deeper and explicit projection on agro-thermal resources dynamic for double-season rice can be done in the further step given more emission scenarios are available.

The thermal resource was a primary factor affecting rice development although water and radiation resources were also important. Future climate changes would also alter distribution of water resources and drought stress (Piao et al. 2010; Ma et al. 2013; Barnwal and Kotani 2013). Irrigation requirements had been predicted to increase to 100 mm under RCP8.5 for the 2080s (Ding et al. 2017). Therefore, varieties with enhanced drought tolerance would be needed. However, the unavoidable bias for these climate models suggests that future deeper and explicit research could result in more reliable predictions.

5 Conclusions

The current study utilized the top 5 climate models at a high resolution to assess potential changes of agro-thermal resources in terms of SSd, SMd, PGS, and GAT10 for the double-season rice planting region in China. Relative to 2001–2015, earlier magnitude of SSd, later magnitude of SMd, and longer magnitude of PGS in the future periods were projected under RCP8.5, in comparison with that under RCP4.5. It was highlighted that the prolongation of SMd made a greater contribution to a longer PGS compared with SSd. This was merely documented before and could be an important condition for adapting rice cultivation to a changing climate. Importantly, GAT10 increases would continue in the future especially in southern parts of China. These changes can serve for the adaptation of specific rice production management practices such as an earlier sowing time, later maturation time, and the use of new rice varieties that match these thermal requirements, in response to the possible change of climate in the future.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-021-03519-x.

Authors' contribution Lei Zhang and Sen Li conceived the topic of the work. Fangying Tan and Anhong Guo archived the datasets and drew the figures. Lei Zhang drafted the manuscript, and Zhiguo Huo revised the manuscript.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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