atmosphere

MDPI

Article

Asymmetric Differences in the Effects of Average Air Temperature and Solar Radiation on Early Rice and Late Rice Yield

Shengbao Wei, Anchun Peng †, Jing Liu, Dongxian Wei and Changqing Chen *

Jiangsu Collaborative Innovation Center for Modern Crop Production, Nanjing Agricultural University, Nanjing 210095, China; 2019101014@njau.edu.cn (S.W.); 2020101021@stu.njau.edu.cn (A.P.); 2018101004@njau.edu.cn (J.L.); 2020801195@stu.njau.edu.cn (D.W.)

* Correspondence: cn828@njau.edu.cn

† Contribute equally as first authors.

Abstract: China is the world's largest rice producer. Thus, the stability of rice production plays a decisive role in food security. Among the types of rice, double rice (including early rice and late rice) accounts for the largest proportion of rice in China. Climate change is widely expected to affect rice yields. Studying the response of double rice yield to climate change will benefit strategic decisions related to future crop adaptation. In this paper, the relationship between climate factors and the yield of double rice during 1992–2013 in south China was analysed to determine the responses of double rice yield to climate change. The results showed that the daily average air temperature during the early rice and late rice growing seasons increased by 0.34 °C and 0.68 °C, 0.29 °C and 0.67 °C, and 0.11 °C and 0.31 °C per 10-year period in the northern subtropical zone (NST), middle subtropical zone (MST) and south subtropical zone (SST), respectively, in the last 20 years. The change trend in solar radiation was not obvious, but it fluctuated greatly. A 1 °C increase in average air temperatures decreased early rice yield by 5.36% and 2.16% in SST and MST, respectively; decreased late rice yield by 0.75% and 1.43% in MST and NST, respectively; and increased late rice yield by 3.93% in SST. A solar radiation increases of 100 MJ m^{-2} increased early rice yield by 1.02%, 1.54% and 1.71% in SST, MST and NST, respectively, and decreased late rice yield by 0.89% in SST. We found that annual average temperatures of 17.3 °C and 18.6 °C were the early rice and late rice yield variation thresholds, respectively; in addition, above the background temperature in south China, the early rice yield will decrease and the late rice yield will increase.

Keywords: double rice; average air temperature; solar radiation; climate warming

Citation: Wei, S.; Peng, A.; Liu, J.; Wei, D.; Chen, C. Asymmetric Differences in the Effects of Average Air Temperature and Solar Radiation on Early Rice and Late Rice Yield. *Atmosphere* **2021**, *12*, 1541. https://doi.org/10.3390/atmos12121541

Academic Editors: Gianni Bellocchi and Christos Zerefos

Received: 30 August 2021
Accepted: 13 November 2021
Published: 23 November 2021

1. Introduction

Environmental change has been shown to represent a major influence on global food security. Crop adaptation strategies to address global climate change should focus more on future warming [1]. Rice is an important staple food crop worldwide, and an estimated increased production rate of 8–10 million tons per year will be necessary to meet the world's demand in the next decade, which will require an annual yield increase of 1.2–1.5% without expanding the cultivated area [2]. In China, an additional 20% yield will be required before 2030 to feed its population, even if the consumption per capita remains at the current level [3]. However, if the present structure of rice cropping systems persists, climate warming will reduce China's total rice production by 5.0% in 2060 [4]. Moreover, the limited cultivation area and the shrinking future cultivation areas emphasize the need to increase the productivity of Chinese crops [5,6]. Because the magnitude and range of these changes are very uncertain, the prediction of climate change effects on rice yield is difficult and speculative. Although speculative, many published papers have suggested potential problems that could occur under climate change.

Rice production is significantly affected by climatic factors such as precipitation, temperature, solar radiation, and relative humidity [7]. In China, the double rice cropping system consists of early rice and late rice, the early and late rice seedlings were transplanted to the paddy in April and July, and harvested in July and October, respectively. The yield of early rice was mainly affected by the high temperatures during the vegetative stage and low daily minimum temperatures during the ripening period, whereas the high daily solar radiation during the reproductive and ripening periods was critical for the yield performance of the late rice [8]. Zhang et al. [9] analyzed the data collected from the experimental stations, and the results showed that rice yields were positively correlated with the maximum air temperature, the minimum air temperature, and the average air temperature at most stations. Of the sowing dates, the impact of solar radiation on early rice transplantation was lower than that on late transplanted rice, while the reverse trend was observed for sunshine duration. The effect of maximum and minimum temperatures during the early rice vegetative period was also higher than that during the late rice vegetative period [10]. Temperature and precipitation are the main climatic constraints on crop production efficiency, the increases of incident solar radiation can improve the above-ground biomass [11], and the cumulative solar radiation during the reproductive stages could have a positive contribution to yield. Stable yields can be obtained when there is stable solar radiation in a large rainfall environment [12]. The mean daily temperature and mean daily solar radiation in the whole growth duration have a significant positive correlation with rice yield and harvest index [13].

Studies have documented that increasing temperature could shorten crop growth duration and reduce crop yields across rice growing areas [14]. As the temperature warms, the actual yield, yield potential and yield gap of rice show obvious spatiotemporal pattern changes. Rice yield has shown an increasing trend in more than 95% of the studied sites. The yield potential in northeast China has increased over the past three decades because of the increase in temperature, while the increased temperature and decreased solar radiation have reduced the yield potentials in other regions [11]. The effects of temperature and solar radiation on rice yield have been studied, but their effectiveness in different regions, as well as how temperature and solar radiation may influence these strategies, remains unclear. Temperature increases contribute significantly to a decline in rice yield because a higher temperature will increase rice plant respiration rates and reduce net photosynthesis and consequently lower biomass production and yield [15,16].

To a major extent, solar radiation determines plant photosynthesis and related terrestrial carbon uptake, the heat balance of agricultural surfaces and hence the temperatures of crop canopies, soil, and air, and solar radiation has been reported to be the major factor regulating the growth of crops [17]. Therefore, any significant change in global radiation is likely to have major practical implications for climate change and for agricultural production [17,18]. The number of hours of sunshine during the tillering stage and the heading to milk stage particularly affect the yield. In both periods, radiation is low. In the first period, the vegetative organs of the rice crop are formed, while in the second period, solar radiation is important for grain filling. The average temperature during the tillering to jointing stage reaches its maximum, which negatively affects rice yields [19]. Solar radiation is one of the most dominant meteorological factors influencing grain yields in crop plants, including rice [16,20], and its effect, particularly during the reproductive stage, is critical [21]. Pollution has increased the average global surface temperature and decreased solar radiation, which in turn have increased the frequency of environmental stresses, such as heat stress and solar dimming, and hence adversely affected the growth and yield of crops [22–25].

In the past three decades, decreases in solar radiation reduced rice yield by 0.96%, 0.13%, 9.34% and 6.02% [26]. There are also great differences in rice growth in southern China. Many studies only analyse the relationship between double rice yield and climate in the south. However, due to the diverse geographical conditions and the large differences in climate at different latitudes, we mainly discuss the effects of temperature and radiation changes in the three subtropical climatic zones of south China on the yield of double rice. The main objectives were to analyse (1) historical trends in daily mean air temperatures and solar radiation during the double rice growing season in three regions and (2) regional differences in the response of double rice yield to temperature and solar radiation.

2. Materials and Methods

2.1. Research Area

Double rice is a crop in the subtropical region of southern China, but double rice grown with different manifestations due to geographical difference. Thus, we divided the subtropical zone into the northern subtropical zone (NST), the mid-subtropical zone (MST), and the southern subtropical zone (SST) (Figure 1). The NST is located at 28° N to 33° N, including Hubei, Anhui, and Zhejiang provinces. The average temperature in January is 0–5 °C, the average temperature in July is 24–29 °C, and the absolute minimum temperature is greater than −20 °C. The accumulated temperature at 10 °C or above is approximately 4500–5400 °Cd. The frost-free period is approximately 200–250 days. The MST is approximately at 24° N–28° N, including Fujian, Jiangxi and Hunan provinces. The annual precipitation in this climatic zone is generally abundant, mostly from 1000 to 1500 mm. The coldest average temperature is approximately 2–8 °C. The SST is located in south China, including Guangdong and Guangxi provinces. The frost-free season occurs for more than 300 days. The average temperature of the coldest month is above 10 °C, while the annual accumulated temperature is 6500–8000 °C. Specific climate information is shown in Table 1.

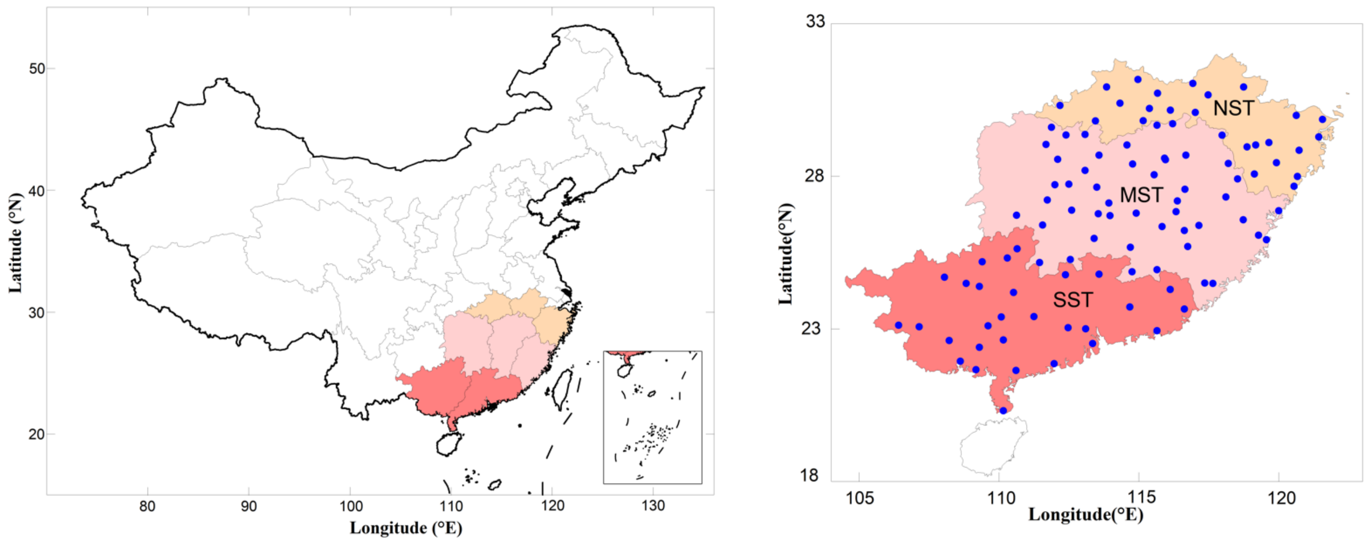

Figure 1. The research area and spatial distribution of climate observation stations. NST, MST and SST indicate the northern subtropical zone, middle subtropical zone and south subtropical zone, respectively.

Table 1. Climatic conditions in the three climatic zones (1992–2013).

Region	Tavg		Tmax		Tmin		Prec		SSD	
	Mean ± SD (°C)	Trend (°C yr^{-1})	Mean ± SD (°C)	Trend (°C yr^{-1})	Mean ± SD (°C)	Trend (°C yr^{-1})	Mean ± SD (mm)	Trend (mm yr^{-1})	Mean ± SD (h)	Trend (h yr^{-1})
NST	16.31 ± 0.47	0.033	21.96 ± 0.53	0.033	13.79 ± 0.46	0.032	1414.9 ± 172.1	−0.640	1751.7 ± 94.59	−3.191
MST	18.37 ± 0.43	0.033	23.16 ± 0.50	0.030	14.98 ± 0.39	0.031	1579.2 ± 217. 9	−3.407	1556.4 ± 115.9	−0.861
SST	21.73 ± 0.41	0.019	26.27 ± 0.43	0.013	18.58 ± 0.39	0.020	1745. 3 ± 230.3	−0.866	1647.4 ± 115.4	1.300

SD means standard deviation; NST, MST and SST indicate the northern subtropical zone, middle subtropical zone and south subtropical zone, respectively. Tavg, Tmax, Tmin, Prec, and SSD correspond to the average air temperature, maximum air temperature, minimum air temperature, precipitation, and sunshine duration, respectively. °C yr^{-1}, mm yr^{-1} and h yr^{-1} indicate 1 °C per year, 1 mm per year and 1 h per year, respectively.

2.2. Data Analysis

2.2.1. Calculation of Global Solar Radiation from Sunshine Duration

There were two datasets in this study. First, climatic data were collected based on the completeness of records, including air temperatures (daily average, maximum and minimum temperatures) and daily sunshine duration, from 1992 to 2013 from the Chinese Meteorological Administration [27]. 101 meteorological observation stations were selected across the region, with 26 stations in NST, 44 stations in MST, and 31 stations in SST (Figure 1). The climatic data were described during double rice growth stages.

Since only a few stations have data on solar radiation, empirical formulas were used to calculate the daily solar radiation of each station. The model was mainly based on the relationship between the total solar radiation measured at the existing stations for many years and the percentage of sunshine and the upper atmosphere radiation [28,29]. An empirical formula was established for calculating total solar radiation in different regions:

$$Q = Q_0\ (a + b * S/S_0) \tag{1}$$

Q is the total daily radiation value, Q_0 is the daily astronomical radiation value, a and b are the coefficients, S is the actual sunshine hours, and S_0 is the sunshine hours. Q_0 is calculated according to the following formula [30]:

$$Q_0 = T/\pi * I_0\ /\rho^2 * (\omega_0\ sin\ \varphi\ sin\ \delta + cos\ \varphi\ cos\ \delta\ sin\ \omega_0) \tag{2}$$

I_0 is the solar constant, I_0 = 4.921 MJ m^{-2}; T is 24 h per day; ρ is the relative distance between the Sun and the Earth; ω_0 is the sunrise and sunset time angle; φ is the geographical latitude; and δ is the solar declination.

At present, there are 23 climate observation stations of China Meteorological Administration with data records of solar radiation and sunshine hours in the study area. Based on the observed solar radiation values and sunshine percentages at 19 sites in the study area using Equation (1) and regression analysis, the values of a and b in this area were estimated, and the slope, the intercept, the coefficient of determination (R^2) of the regression lines, root mean square error (RMSE), and relative root square error (RRMSE), were used to calculate the accuracy of the calculated solar radiation [31]. The fitted coefficients a, b, RMSE, RRMSE, and R^2 between observed daily global solar radiation and calculated daily global solar radiation are summarized in Table 2.

Table 2. Fitted coefficients a, b, RMSE (MJ m^{-2} day^{-1}), RRMSE (%), and R^2 between observed daily global solar radiation and calculated daily global solar radiation for the study regions.

Region	NST	MST	SST
a	0.175	0.159	0.180
b	0.571	0.551	0.527
RMSE (RRMSE)	2.53 (19.28)	2.63 (21.32)	2.38 (17.18)
R^2	0.889	0.878	0.893

NST, MST, and SST indicate the northern subtropical zone, middle subtropical zone and south subtropical zone, respectively.

2.2.2. The Impact of Weather Factors on Rice Yield

Historical rice grain yields at a province scale were the second dataset, collected from the China Rural Statistical Yearbook [32] between 1992 and 2013. The average yields of each sub-region were calculated by the ratio of the rice yields to the rice cropping area of these included provinces. These province-level yields were matched with various weather measurements from 1992–2013. The weather in a province was the weighted average of all meteorological observation stations that fall in a province. The crop yield was impacted by various climatic and non-climatic factors (e.g., anthropogenic factors) and showed trends due to improvements in technological progress [33]. Generally, the crop yield exhibited highly timely nonlinear trends. Therefore, a 2nd-order polynomial was a reasonable compromise for fitting the regression equations. Thus, our regression equation linked log yields *y(i,t)* as yields followed a log-normal distribution, and yield variance stayed comparable in relative, but not absolute terms, in province *i* in year *t* to various specifications of weather *X(i,t)* that have been used in some literature. The model is expressed in the following form:

$$y\ (i,\ t) = ci + d_1 i * year + d_2 i * year^2 + \beta * X\ (i,\ t) + \varepsilon\ (i,\ t) \quad (3)$$

All regressions included a quadratic time trend (to capture overall technological progress) as well as province fixed effects (*ci*); $d_1 i$ is the province-specific linear time trend; $d_2 i$ is the province-specific quadratic time trend; and β is a vector of coefficients of weather *X (i, t)*. Weather *X (i, t)* is a linear specification including the mean, maximum or minimum temperature as well as total sun radiation during the growing season. All statistical analyses were conducted using R language 2.11.1 and Eviews 6.0 (HIS Eviews, Irvine, CA, USA) statistical analysis software.

3. Results

3.1. Historical Trend of Global Warming during Double Rice Growing Season

The average temperature of the early rice growth period increased by 0.034 °C, 0.029 °C and 0.011 °C per year in the three climate zones of NST, MST and SST during 1992–2013, respectively (Figure 2a–c). In MST and SST, the solar radiation increased in the early rice growth period by 1. 772 MJ m^{-2} and 2.631 MJ m^{-2} per year, respectively, but the solar radiation in NST was reduced by 0.957 MJ m^{-2} per year with larger fluctuations than those in the other areas (Figure 2d–f). The average temperature of the late rice growth period increased by 0.068 °C yr^{-1}, 0.067 °C yr^{-1} and 0.031 °C yr^{-1} for NST, MST and SST, respectively (Figure 3a–c). In MST and SST, the solar radiation increased by 4.278 MJ m^{-2} and 2.487 MJ m^{-2}, respectively, but the solar radiation was reduced by 3.516 MJ m^{-2} per year in NST (Figure 3d–f).

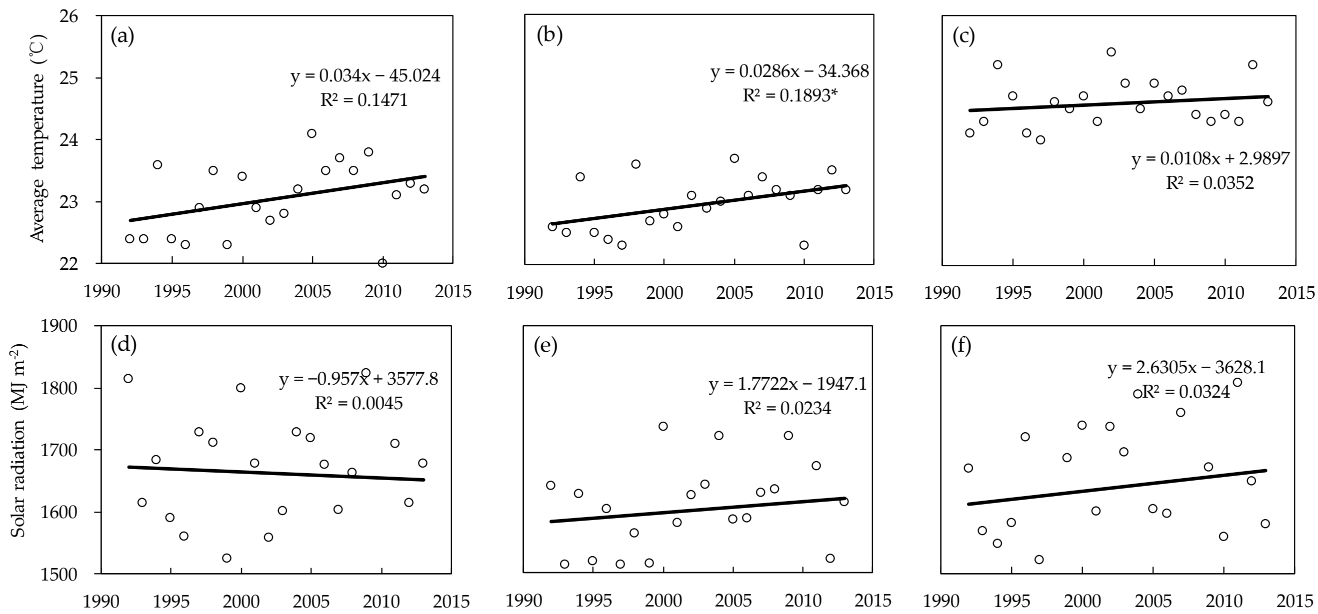

Figure 2. Trends in average temperature (**a**–**c**) and solar radiation (**d**–**f**) of the early rice growth period in the three climatic zones. (**a**,**d**), (**b**,**e**), and (**c**,**f**) indicate the northern subtropical zone (NST), middle subtropical zone (MST) and south subtropical zone (SST), respectively. * Significant at $p < 0.05$.

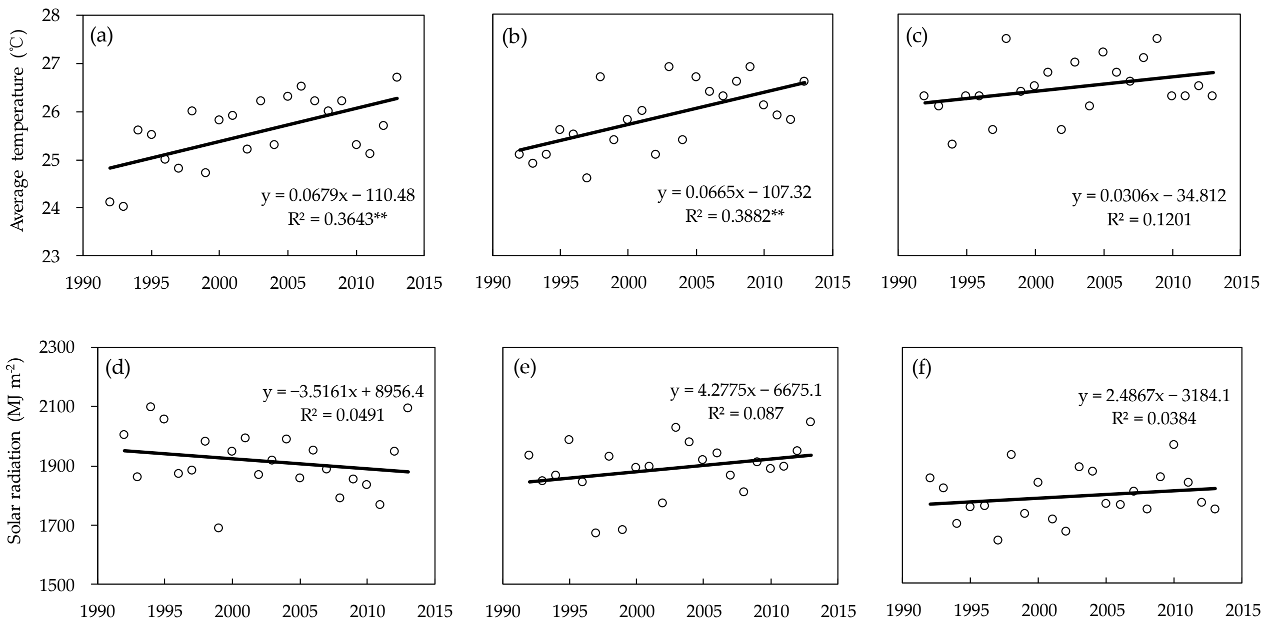

Figure 3. Trends in average temperature (**a**–**c**) and solar radiation (**d**–**f**) of the late rice growth period in the three climatic zones. (**a**,**d**), (**b**,**e**), and (**c**,**f**) indicate the northern subtropical zone (NST), middle subtropical zone (MST) and south subtropical zone (SST), respectively. ** Significant at $p < 0.01$.

3.2. Historical Trend in Yield of Double Rice

The historical yield trends in double rice from 1992 to 2013 were analysed with linear regression. The yield of early rice in the NST and MST increased significantly by 21.84 kg ha^{-1} and 47.65 kg ha^{-1} per year, respectively, but the yield of SST early rice decreased by 6.58 kg ha^{-1} per year (Figure 4). The yield of late rice in the MST and SST increased significantly by 13.89 kg ha^{-1} and 17.63 kg ha^{-1} per year, respectively. However, the yield change was not significant in NST (Figure 5).

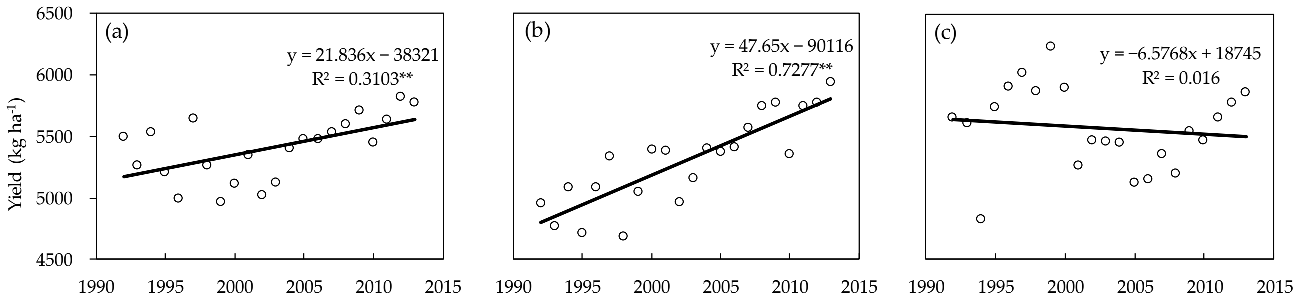

Figure 4. Trends in the yield of early rice in the three climatic zones. (**a**–**c**) indicate the northern subtropical zone (NST), middle subtropical zone (MST) and south subtropical zone (SST), respectively. ** Significant at $p < 0.01$.

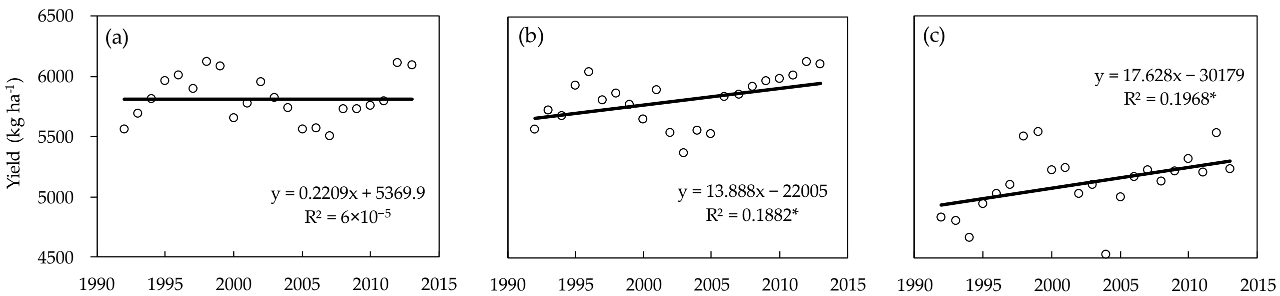

Figure 5. Trends in the yield of late rice in the three climatic zones. (**a**–**c**) indicate the northern subtropical zone (NST), middle subtropical zone (MST) and south subtropical zone (SST), respectively. * Significant at $p < 0.05$.

3.3. Responses of Double Rice Yield to Average Temperature Rise

The average air temperatures rose by 1 °C decreasing early rice yield by 5.36% and 2.16% in SST and MST, respectively. A slight increase was observed in NST (Figure 6a). Moreover, the average air temperature rose 1 °C decreasing late rice yield by 0.75% and 1.43% in MST and NST, respectively. However, the average temperature increased the yield by 3.93% in SST (Figure 6b). The increase in the temperature in the early rice growth period was not conducive to yield, while the increase in temperature in the late rice growth period was conducive to rice yield in southern China and not conducive to rice yield in northern China.

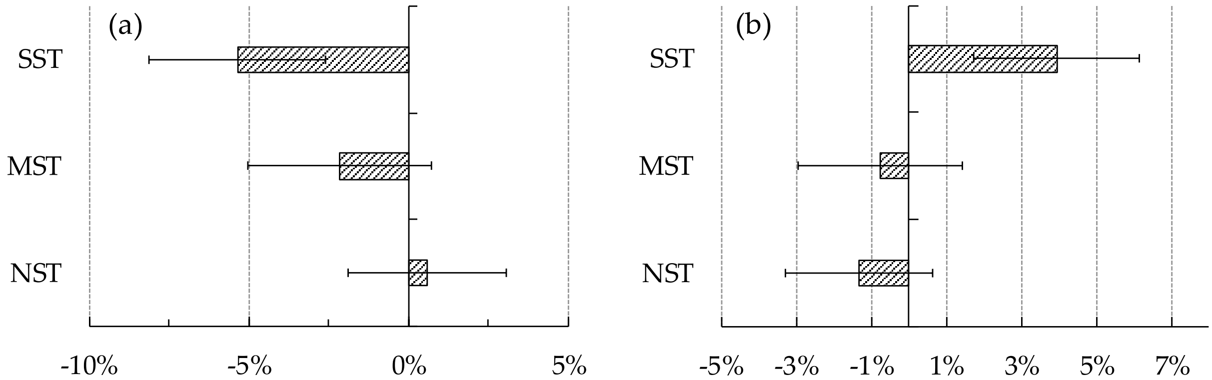

Figure 6. Effect of average temperature on double rice yield. (**a**) early rice; (**b**) late rice. NST, MST and SST indicate the northern subtropical zone, middle subtropical zone and south subtropical zone, respectively. (early rice: R^2 = 0.293, p = 0.036; late rice: R^2 = 0.401, p < 0.001, n = 66).

3.4. Responses of Double Rice Yield to Solar Radiation

Solar radiation had positive effects on late rice yields, and the solar radiation increased by 100 MJ m^{-2}, increasing yields by 1.02%, 1.54% and 1.71% in SST, MST and NST, respectively. More to the north, the effects of radiation on increasing yield were more obvious (Figure 7b). However, for early rice yield, solar radiation had a negative impact in SST with −0.89% in yield per 100 MJ m^{-2} increase in radiation, and there was a small impact in NST and MST (Figure 7a).

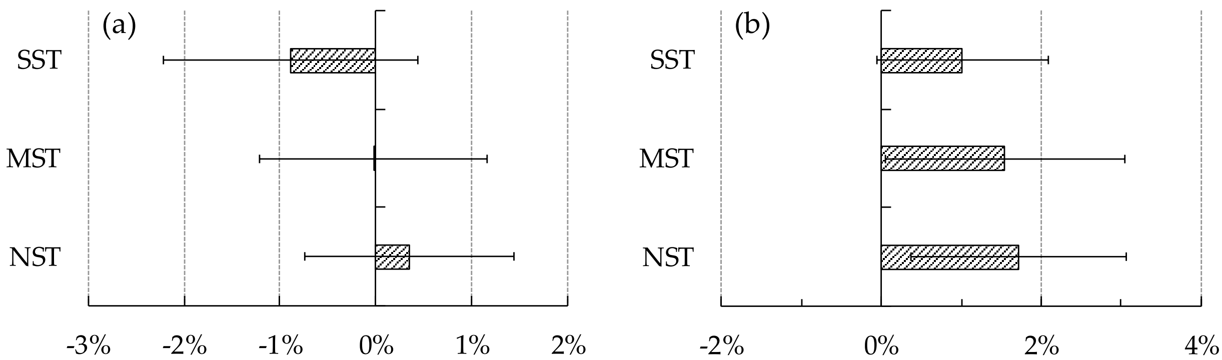

Figure 7. Effect of solar radiation on double rice yield. (**a**) early rice; (**b**) late rice. NST, MST and SST indicate the northern subtropical zone, middle subtropical zone and south subtropical zone, respectively. (early rice: R^2 = 0.293, p = 0.0456; late rice: R^2 = 0.401, p < 0.001, n = 66).

3.5. Relationship between Annual Average Temperature and Double Rice Yield Change Rate

The relationship between annual average temperature and double rice yield change rate was analyzed by calculating the rice yield change rate of 9 provinces of South China and the annual average temperature of each province (Figure 8). The early rice yield increased in the north and decreased in the south, and the late rice yield increased in the south and decreased in the north, which demonstrated the climate impacts on double rice yield. Therefore, we analysed the relationship between annual average temperature and yield impact rate. The equations showed that the 17.3 °C annual average temperature was the split point that affected the increase or decrease in early rice yield (Figure 8a). The early rice yield decreased at temperatures over 17.3 °C and increased at temperatures below 17.3 °C. However, for late rice, the yield change rate increased with increasing annual average temperature (Figure 8b). When the annual average temperature was greater than 18.6 °C, the yield change rate was positive. However, it was negative below 18.6 °C. The annual average temperature increased yearly. When the temperature increased to 17.3 °C ~18.6 °C in any location, both the early rice and late rice yields decreased. Before the annual average temperature reached 17.3 °C, it has a positive effect on early rice yield, but it decreased the yield of late rice. The annual average temperature exceeded 18.6 °C, which decreased early rice yield and increased late rice yield.

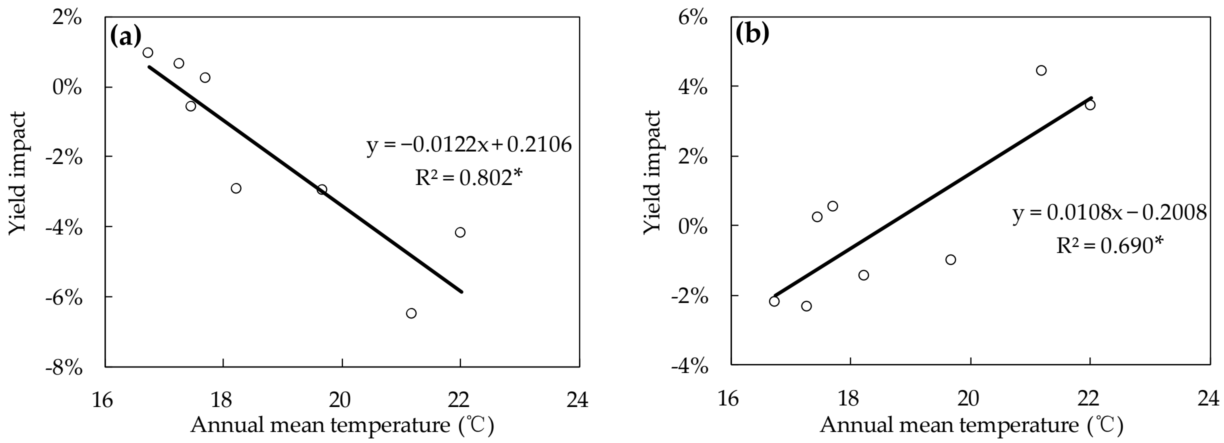

Figure 8. Relationship between annual average temperature and double rice yield change rate. (**a**) early rice; (**b**) late rice. * Significant at $p < 0.05$.

4. Discussion

Among climatic parameters, crop yields are largely influenced by air temperature and solar radiation [1,34]. Studies have shown that warming can have a positive or negative impact on crop yields. For example, Chen and Tian [35] found that the positive effect of daily minimum temperature on rice yield varies with rice growth stage, increased T_{min} had a large and positive impact on early rice yield during the ripening stage, while the positive effect of T_{min} on late rice Yield occurred during the reproductive stage. Zhang et al. [36] also found that higher T_{min} increased late rice yield by decreasing cold stress. However, Peng et al. [23] reported that rice yield declined by 10% for each 1 °C increase in growing-season minimum temperature when it was above 22 °C. In addition, temperature changes are not conducive to the accumulation of dry matter, high temperatures may reduce biomass production and grain yield by accelerating the rate of development and thus shorten crop growth duration, which ultimately restrict the formation of rice yield [37–39]. Consistent with previous work, the average temperature significantly increased in the NST and MST regions within the scope of our research. The average temperature has increased by 0.6–1.3 °C in the past 20 years during the double rice growth period, and warming in the north is obviously higher than that in the south. In our study, we observed that the response of early and late rice yields to the average air temperature rise have differences among different regions, and this is consistent with previous studies, which found that for late rice, the average temperature rise has a positive effect on the southern region of South China, but has a negative effect in the northern region, while early rice was just opposite [40]. The average temperature increased during the crop growth period resulting in a negative impact on early rice yield but a positive impact on late rice yield in SST. The average temperature during the later growth stage of early rice was higher than that during the other stages and continued to increase, Zhao et al. [41] found that the dates of heading and maturity for early rice were negatively associated with the average temperature in each growth period, temperature increases contribute significantly to the decline in early rice yield because higher temperatures increase the early rice respiration rate and reduce net photosynthesis and consequently result in lower biomass production and yield [15]. However, the mean temperature in NST had a positive effect on the yield of early rice, whereas had the opposite effect on late rice. This may be related to the lower average temperature in the late growth period of early rice in the NST region, and the elevated temperatures contributed to increased early rice yields but led to substantial extreme heat risks during late rice production. The temperature in MST had a slight negative impact on the double rice. Over the past 20 years, this result has mainly been due to the increase in average temperature during the growth period of early rice within optimum temperature ranges [42]. During the growth of late rice, a high the rate of temperature increase at night increases respiratory consumption, which is not conducive to the growth and yield formation of late rice.

At the same time, higher grain yield is generally associated with higher incident solar radiation and higher intercepted solar radiation by the rice crop canopy [43]. Solar radiation is one of the most dominant meteorological factors influencing grain yields [44–46], and its effect, particularly during the reproductive stage, is critical [21,23]. Solar radiation has a significant effect on yield and yield components [47], and some researchers have found that there is a significant positive relation between solar radiation and yield [48]. An increase in solar radiation causes an increase in rice yield [49]. In addition, decreases in solar radiation reduce rice yield, resulting in overall negative climate impacts on yield [38,50]. Previous studies have shown that the mean daily temperature and mean daily solar radiation during the entire growth period showed a significant positive correlation with rice yield, total dry matter, and harvest index [13]. We found that the change trend in solar radiation was not obvious, but it fluctuated greatly, which greatly affected crop yield. The temperature decreased gradually during the reproductive growth stage of late rice and was very suitable for development and grain filling in the three regions. Therefore, an increase in solar radiation would increase late rice yields. However, high temperatures gradually increased during the reproductive growth period of early rice, and photosynthesis was weakened due to the increase in photorespiration at high temperatures. Consequently, the early rice yield was reduced in SST, as the air temperature increased faster than that in the other two regions. Solar radiation primarily determines photosynthesis and related terrestrial carbon uptake. Therefore, any significant change in global radiation is likely to have major practical implications for climate change and agricultural production [17,18]. The high average rice yield level and the good response of rice to N fertilizer application were attributed to high solar radiation levels [18,23]. Cumulative solar radiation during reproductive stages could have a positive impact on yield at the right temperature. Stable yields can be obtained when there is stable solar radiation. However, the response of rice yield to solar radiation is not always consistent (Figure 7), especially early rice is more likely to affect by climate change. The positive correlation between early rice yield and radiation, average temperature and maximum temperature all depend on rainfall [51]. Abundant precipitation has no significant positive impact on yield, but due to the increases in rainy days reduced solar radiation and the optimum temperature for rice growth, which caused a significant negative impact on early rice yield [51]. In addition, the early rice yield is impacted more by temperature while solar radiation has a greater effect on late rice yield [8], the early transplanted plants could not effectively utilize solar radiation for CO_2 assimilation, and that early biomass production was constrained by low temperature [52]. Overall, the interference of other factors such as temperature and rainfall may be an important factor affecting the relationship between solar radiation and early rice yield. Therefore, the influence of other factors should be fully considered in in future studies to comprehensively analyze the relationship between rice yield and solar radiation.

5. Conclusions

There was a different response of double rice yield to temperature increase and solar radiation change. An average temperature increase can increase the late rice yield but decrease the early rice yield in SST. An opposite result occurred in NST. Increasing solar radiation significantly increased early rice yield in the three sub-regions. Responses of early and late rice yields to temperature are correlated with background temperature in the region. The yield change rate of early rice and late rice may be opposite after reaching the background temperature value.

Author Contributions: Conceptualization, C.C.; methodology, C.C. and S.W.; software, S.W. and A.P.; validation, A.P. and J.L.; formal analysis, A.P. and J.L.; investigation, J.L. and D.W.; resources, C.C.; data curation, S.W. and A.P.; writing—original draft preparation, S.W. and A.P.; writing—review and editing, J.L. and D.W.; project administration, C.C.; funding acquisition, C.C. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Key Research and Development Program of China (2016YFD0300501, 2016YFD0300905 and 2015BAC02B02), Special Fund for Agro-scientific Research in the Public Interest (201503122), Central Public Interest Scientific Institution Basal Research Fund of Institute of Crop Science, and the Innovation Program of CAAS (Y2016PT12 and Y2016XT01).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Wang, D.; Laza, M.R.C.; Cassman, K.G.; Huang, J.; Nie, L.; Ling, X.; Centeno, G.S.; Cui, K.; Wang, F.; Li, Y.; et al. Temperature explains the yield difference of double-season rice between tropical and subtropical environments. *Field Crop. Res.* **2016**, *198*, 303–311. [CrossRef]
2. Seck, P.; Diagne, A.; Mohanty, S.; Wopereis, M. Crops that feed the world 7: Rice. *Food Secur.* **2012**, *4*, 7–24. [CrossRef]
3. Peng, S.; Tang, Q.; Zou, Y. Current Status and Challenges of Rice Production in China. *Plant. Prod. Sci.* **2009**, *12*, 3–8. [CrossRef]
4. Chen, C.; van Groenigen, K.J.; Yang, H.; Hungate, B.A.; Yang, B.; Tian, Y.; Chen, J.; Dong, W.; Huang, S.; Deng, A.; et al. Global warming and shifts in cropping systems together reduce China's rice production. *Glob. Food Secur.-Agric. Policy* **2020**, *24*, 100359. [CrossRef]
5. Lu, C.; Fan, L. Winter wheat yield potentials and yield gaps in the North China Plain. *Field Crop. Res.* **2013**, *143*, 98–105. [CrossRef]
6. Zhang, T.; Yang, X.; Wang, H.; Li, Y.; Ye, Q. Climatic and technological ceilings for Chinese rice stagnation based on yield gaps and yield trend pattern analysis. *Glob. Chang. Biol.* **2014**, *20*, 1289–1298. [CrossRef]
7. Ji, B.; Sun, Y.; Yang, S.; Wan, J. Artificial neural networks for rice yield prediction in mountainous regions. *J. Agric. Sci.* **2007**, *145*, 249–261. [CrossRef]
8. Xu, L.; Zhan, X.; Yu, T.; Nie, L.; Huang, J.; Cui, K.; Wang, F.; Li, Y.; Peng, S. Yield performance of direct-seeded, double-season rice using varieties with short growth durations in central China. *Field Crop. Res.* **2018**, *227*, 49–55. [CrossRef]
9. Zhang, T.; Zhu, J.; Wassmann, R. Responses of rice yields to recent climate change in China: An empirical assessment based on long-term observations at different spatial scales (1981–2005). *Agric. For. Meteorol.* **2010**, *150*, 1128–1137. [CrossRef]
10. Chen, Y.; Wang, P.; Zhang, Z.; Tao, F.; Wei, X. Rice yield development and the shrinking yield gaps in China, 1981–2008. *Reg. Environ. Chang.* **2017**, *17*, 2397–2408. [CrossRef]
11. Monteith, J.L. Climate and the efficiency of crop production in Britain. *Philos. Trans. R. Soc. Lond. B* **1977**, *281*, 277–294. [CrossRef]
12. Makahiya, H.A.F.; Perdiguerra, K.N.C.; Marajas, I.R.M.; Edano, M.L.S.; Hernandez, J.E.; Cruz, P.C.S. Analysis of Genotype by Environment Interaction in Irrigated Lowland Rice (*Oryza sativa* L.) Varieties under Diverse Agroclimatic Environments. *Philipp. J. Crop Sci.* **2017**, *42*, 28–36.
13. Xing, Z.; Wu, P.; Zhu, M.; Qian, H.; Hu, Y.; Guo, B.; Wei, H.; Xu, K.; Huo, Z.; Dai, Q.; et al. Temperature and solar radiation utilization of rice for yield formation with different mechanized planting methods in the lower reaches of the Yangtze River, China. *J. Integr. Agric.* **2017**, *16*, 1923–1935. [CrossRef]
14. Porter, J.R.; Xie, L.; Challinor, A.J.; Cochrane, K.; Howden, S.M.; Iqbal, M.M.; Lobell, D.B.; Travasso, M.I. 2014: Food security and food production systems. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., et al., Eds.; IPCC, Cambridge University Press: Cambridge, UK; New York, NY, USA, 2014; pp. 485–533.

15. Xiao, G.; Zhang, Q.; Li, Y.; Wang, R.; Yao, Y.; Zhao, H.; Bai, H. Impact of temperature increase on the yield of winter wheat at low and high altitudes in semiarid northwestern China. *Agric. Water Manag.* **2010**, *97*, 1360–1364. [CrossRef]
16. Molua, E.; Lambi, C. *Assessing the Impact of Climate on Crop Water Use and Crop Water Productivity: The CROPWAT Analysis of Three Districts in Cameroon*; University of Pretoria: Pretoria, South Africa, 2006; p. 44.
17. Stanhill, G.; Cohen, S. Global dimming: A review of the evidence for a widespread and significant reduction in global radiation with discussion of its probable causes and possible agricultural consequences. *Agric. For. Meteorol.* **2001**, *107*, 255–278. [CrossRef]
18. Wild, M.; Ohmura, A.; Makowski, K. Impact of global dimming and brightening on global warming. *Geophys. Res. Lett.* **2007**, *34*, L04702. [CrossRef]
19. Yu, Q.; Hengsdijk, H.; Liu, J.D. Application of a progressive-difference method to identify climatic factors causing variation in the rice yield in the Yangtze Delta, China. *Int. J. Biometeorol.* **2001**, *45*, 53–58. [CrossRef]
20. Walton, J.R. Crop Evolution, Adaptation and Yield by L. T. Evans. *Agric. Hist. Rev.* **1998**, *46*, 223.
21. Yoshida, S. *Fundamentals of Rice Crop Science*; International Rice Research Institute, Laguna: Los Baños, CA, USA, 1981; p. 269.
22. Liepert, B.G. Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990. *Geophys. Res. Lett.* **2002**, *29*, 61-1–61-4. [CrossRef]
23. Peng, S.B.; Huang, J.L.; Sheehy, J.E.; Laza, R.C.; Visperas, R.M.; Zhong, X.H.; Centeno, G.S.; Khush, G.S.; Cassman, K.G. Rice yields decline with higher night temperature from global warming. *Proc. Natl. Acad. Sci. USA* **2004**, *101*, 9971–9975. [CrossRef]
24. Kumari, B.P.; Londhe, A.L.; Daniel, S.; Jadhav, D.B. Observational evidence of solar dimming: Offsetting surface warming over India. *Geophys. Res. Lett.* **2007**, *34*, L21810. [CrossRef]
25. Ambavaram, M.M.R.; Basu, S.; Krishnan, A.; Ramegowda, V.; Batlang, U.; Rahman, L.; Baisakh, N.; Pereira, A. Coordinated regulation of photosynthesis in rice increases yield and tolerance to environmental stress. *Nat. Commun.* **2014**, *5*, 1–14. [CrossRef]
26. Zhang, S.; Tao, F.; Zhang, Z. Changes in extreme temperatures and their impacts on rice yields in southern China from 1981 to 2009. *Field Crop. Res.* **2016**, *189*, 43–50. [CrossRef]
27. Chinese Meteorological Administration Archives. 2014. Available online: http://new-cdc.cma.gov.cn:8081/home.do (accessed on 15 March 2021).
28. Ångström, A.J.M. Solar and Terrestrial Radiation. *Q. J. R. Meteorol. Soc.* **1924**, *50*, 121–125. [CrossRef]
29. Weng, D.M. The discussion on the climatological calculating method of total solar radiation. *Acta Meteorogica Sinica.* **1964**, *34*, 304–315.
30. Gao, G.D. *Climatology Course*; Meteorological Press: Beijing, China, 1996.
31. Wang, J.; Wang, E.; Yin, H.; Feng, L.; Zhao, Y. Differences between observed and calculated solar radiations and their impact on simulated crop yields. *Field Crop. Res.* **2015**, *176*, 1–10. [CrossRef]
32. National Bureau of Statistic of China. *China Rural Statistical Yearbook*; China Statistic Press: Beijing, China, 2018.
33. Hu, Q.; Buyanovsky, G. Climate effects on corn yield in Missouri. *J. Appl. Meteorol.* **2003**, *42*, 1626–1635. [CrossRef]
34. Zhu, X.; Long, S.P.; Ort, D.R. What is the maximum efficiency with which photosynthesis can convert solar energy into biomass? *Curr. Opin. Biotechnol.* **2008**, *19*, 153–159. [CrossRef]
35. Chen, X.; Tian, G. Impacts of weather variations on rice yields in China based on province-level data. *Reg. Environ. Chang.* **2016**, *16*, 2155–2162. [CrossRef]
36. Zhang, J.; Yao, F.; Hao, C.; Boken, V. Impacts of temperature on rice yields of different rice cultivation systems in southern China over the past 40 years. *Phys. Chem. Earth Parts A/B/C* **2015**, *87–88*, 153–159. [CrossRef]
37. Krishnan, P.; Ramakrishnan, B.; Reddy, K.R.; Reddy, V.R. High-Temperature Effects on Rice Growth, Yield, and Grain Quality, in Advances in Agronomy. *Adv. Agron.* **2011**, *111*, 87–206. [CrossRef]
38. Zhang, T.; Huang, Y.; Yang, X. Climate warming over the past three decades has shortened rice growth duration in China and cultivar shifts have further accelerated the process for late rice. *Glob. Chang. Biol.* **2013**, *19*, 563–570. [CrossRef]
39. Deng, N.; Ling, X.; Sun, Y.; Zhang, C.; Fahad, S.; Peng, S.; Cui, K.; Nie, L.; Huang, J. Influence of temperature and solar radiation on grain yield and quality in irrigated rice system. *Eur. J. Agron.* **2015**, *64*, 37–46. [CrossRef]
40. Liu, S.; Wang, X.; Ma, S.; Zhao, X.; Chen, F.; Xiao, X.; Lal, R.; Zhang, H. Extreme stress threatened double rice production in Southern China during 1981–2010. *Theor. Appl. Climatol.* **2018**, *137*, 1987–1996. [CrossRef]
41. Zhao, H.; Fu, Y.H.; Wang, X.; Zhao, C.; Zeng, Z.; Piao, S. Timing of rice maturity in China is affected more by transplanting date than by climate change. *Agric. For. Meteorol.* **2016**, *216*, 215–220. [CrossRef]
42. Sanchez, P.A.; Ramirez, G.E.; Perez, Y.C. Effects of solar radiation on the varietal response of rice to nitrogen on the coast of Peru. In *Soil Management in Tropical America*; North Carolina State Univ: Raleigh, NC, USA, 1975.
43. Katsura, K.; Maeda, S.; Lubis, I.; Horie, T.; Cao, W.; Shiraiwa, T. The high yield of irrigated rice in Yunnan, China—'A cross-location analysis'. *Field Crop. Res.* **2008**, *107*, 1–11. [CrossRef]
44. Buzzell, R.I. Crop Evolution, Adaptation and Yield. *Crop Sci.* **1998**, *38*, 275–276. [CrossRef]
45. Takai, T.; Matsuura, S.; Nishio, T.; Ohsumi, A.; Shiraiwa, T.; Horie, T. Rice yield potential is closely related to crop growth rate during late reproductive period. *Field Crop. Res.* **2006**, *96*, 328–335. [CrossRef]
46. Loomis, R.S. Crop Evolution, Adaptation and Yield—Evans, Lt. *Agric. Hist.* **1994**, *68*, 87–88.
47. Islam, M.S.; Morison, J.I.L. Influence of solar-radiation and temperature on irrigated rice grain-yield in BANGLADESH. *Field Crop. Res.* **1992**, *30*, 13–28. [CrossRef]

48. Tao, F.; Zhang, Z. Climate Change, High-Temperature Stress, Rice Productivity, and Water Use in Eastern China: A New Superensemble-Based Probabilistic Projection. *J. Appl. Meteorol. Climatol.* **2013**, *52*, 531–551. [CrossRef]
49. Kumar, A.; Tripatih, S.K.; Tripathi, P. Impact of climatic parameters on simulated yield of rice at Faizabad of UP. *J. Agrometeorol.* **2017**, *19*, 363–365.
50. Vijayalakshmi, C.; Radhakrishnan, R.; Nagarajan, M.; Rajendran, C. Effect of solar-radiation deficit on rice productivity. *J. Agron. Crop Sci.-Z. Acker Pflanzenbau.* **1991**, *167*, 184–187. [CrossRef]
51. Yang, L.; Qin, Z.; Tu, L. Responses of rice yields in different rice-cropping systems to climate variables in the middle and lower reaches of the Yangtze River, China. *Food Secur.* **2015**, *7*, 951–963. [CrossRef]
52. Ohsumi, A.; Furuhata, M.; Matsumura, O. Climatic responses of biomass production and grain yield in Japanese high-yielding rice cultivars under different transplanting times. *Field Crop. Res.* **2014**, *168*, 38–47. [CrossRef]