Changes in extreme temperatures and their impacts on rice yields in southern China from 1981 to 2009

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1 **ABSTRACT.** Extreme temperature impacts on field crop are of key concern and
2 increasingly assessed, however the studies have seldom taken into account the
3 automatic adaptations such as shifts in planting dates, phenological dynamics and
4 cultivars. In this present study, trial data on rice phenology, agro-meteorological
5 hazards and yields during 1981-2009 at 120 national agro-meteorological experiment
6 stations were used. The detailed data provide us a unique opportunity to quantify
7 extreme temperature impacts on rice yield more precisely and in a setting with
8 automatic adaptations. In this study, changes in an accumulated thermal index
9 (Growing degree day, GDD), a high temperature stress index ($>35^{\circ}\text{C}$ High
10 temperature Degree Day, HDD), and a cold stress index ($<20^{\circ}\text{C}$ Cold Degree Day,
11 CDD), were firstly investigated. Then, their impacts on rice yield were further
12 quantified by a multivariable analysis. The results showed that in the past three
13 decades, for early rice, late rice and single rice in western part, and single rice in other
14 parts of the middle and lower reaches of Yangtze River, respectively, rice yield
15 increased by 5.83%, 1.71%, 8.73% and 3.49% due to increase in GDD. Rice yield was
16 generally more sensitive to high temperature stress than to cold temperature stress. It
17 decreased by 0.14%, 0.32%, 0.34% and 0.14% due to increase in HDD, by contrast
18 increased by 1.61%, 0.26%, 0.16% and 0.01% due to decrease in CDD, respectively.
19 In addition, decreases in solar radiation reduced rice yield by 0.96%, 0.13%, 9.34%
20 and 6.02%. In the past three decades, the positive impacts of increase in GDD and the
21 negative impacts of decrease in solar radiation played dominant roles in determining
22 overall climate impacts on yield. However, with climate warming in future, the

positive impacts of increase in GDD and decrease in CDD will be offset by increase in HDD, resulting in overall negative climate impacts on yield. Our findings highlight the risk of heat stress on rice yield and the importance of developing integrated adaptation strategies to cope with heat stress.

Keywords: adaptation, agriculture, climate change, crop, extreme climate, impacts

1. Introduction

Rice is the most important staple food of Asians, Africans and Latin Americans (Yoshida, 1981; Peng et al., 1995). China has the second largest area of rice cultivation, accounting for more than one third of total rice production in the world. The risk of rice production to climate change and variability in the world and China has increasingly been of concern (Peng et al., 2004; Porter, 2005; IPCC, 2007; Tao et al., 2008, 2013a,b; Zhang et al., 2010; Gourdj et al., 2013). Previous studies have documented that rice productivity will be vulnerable to climate change in southeastern Asia and southern China (Tao et al., 2008; Lobell et al., 2011), particularly due to extreme high temperature (Yoshida et al., 1981; Horie et al., 1996; Matsui et al., 1997a, 1997b; Jagadish et al., 2007; Tao et al., 2013a; Tao and Zhang, 2013; Sanchez et al., 2014). The frequency of climate extreme events is increasing with ongoing climate change (Porter, 2005; Tubiello et al., 2007; Semenov and Shewry, 2011; Tao et al., 2013b; Zhang et al., 2014). There are increasing efforts to investigate the impacts of extreme temperature on crop growth and yield using control-environmental

45 experiments ([Jagadish et al., 2007](#)), statistical approaches ([Welch et al., 2010](#); [Sun and](#)
46 [Huang, 2011](#); [Lobell et al., 2011](#); [Tao et al., 2013b](#); [Wang et al., 2014](#)), and improved
47 crop simulation models ([Challinor et al., 2005](#); [Tao and Zhang, 2013](#); [Asseng et al.,](#)
48 [2015](#)).

49 Among these studies, the impacts of extreme weather events on field crop in the
50 past few decades are particularly concerned ([Peng et al., 2004](#); [Welch et al., 2010](#);
51 [Lobell et al., 2011](#); [Tao et al., 2013b](#)). However, most of these studies are limited by
52 availability of detailed data on crop phenology and yield. Many of them correlated
53 reported harvest data at county or province scale with seasonal climate during a coarse
54 and fixed crop growth period in the past few decades ([Tao et al., 2008](#); [Sun and Huang,](#)
55 [2011](#)). Furthermore, these climate impacts studies have seldom taken into account the
56 automatic adaptations such as shifts in planting dates, phenological dynamics and
57 cultivars ([Welch et al., 2010](#)). Recently, crop phenology and yield data from 1981 to
58 2009 at hundreds of Chinese agro-meteorological experiment stations become
59 available. These data provide us a unique opportunity to matching of weather with
60 farm-specific planting and harvesting dates and rice growth phases in every year,
61 consequently to investigate the impacts of extreme weather on rice yields more
62 precisely and in a setting with automatic adaptations ([Welch et al., 2010](#)).

63 In this study, using the long-term and most detailed experimental data, we aim to 1)
64 develop a more robust high temperature stress index and cold stress index to describe
65 the observed impacts of extreme temperature on rice yield; 2) investigate the
66 spatiotemporal changes of high temperature stress and cold stress in the past three

decades; and 3) estimate the impacts of high temperature stress and cold stress on rice yield in the past three decades and in the future.

2. Materials and methods

2.1. Study area

The middle and lower reaches of Yangtze River is one of the most important rice production areas in China. The cropping systems in the region mainly include the rotation system of double rice (i.e., the rotation between early rice and late rice), and the rotation system of single rice and winter wheat ([Fig. 1](#)). Due to differences in geographical and climate conditions, the single rice cultivation areas were further grouped into single rice in western part (thereafter, single rice (I)) and single rice in other areas of the middle and lower reaches of Yangtze River (thereafter, single rice (II)).

2.2. Stations and Data

Data on rice phenology, agricultural meteorological disaster events such as high temperature stress and cold stress, and yield from 1981 to 2009 were obtained from China agro-meteorological experiment stations, which are maintained by the China Meteorological Administration (CMA). We used the experimental observations at 41, 40, 17, 22 stations for early rice, late rice, single rice (I), and single rice (II), respectively ([Fig.1](#)). According to the experimental observations, rice cultivars were shifted quite frequently, irrigation and fertilizer were used every year. Rice

transplanting date, heading date, flowering date, maturity date and yield at each station from 1981 to 2009 were included in the dataset. The detailed phenological records were used for matching of weather variables with transplanting, flowering and harvesting dates and consequently rice growth phases in every year. Heat and cold stress hazards at these agro-meteorological stations were recorded by local agronomists.

Daily weather data on mean temperature (T_{mean}), maximum temperature (T_{max}), minimum temperature (T_{min}) and sunshine duration from 1981 to 2009 at these stations were also obtained from CMA. The daily solar radiation (SRD) was calculated from daily sunshine duration observation with the Angstrom-Prescott equation ([Prescott, 1940](#)).

2.3. Calculation of Growing Degree Days (GDD), High temperature Degree Days (HDD) and Cold Degree Days (CDD) during rice growth period

Growing degree days (GDD) were calculated as the methods used by CERES-Rice model in DSSAT 4.5 ([Jones et al., 2003](#)). It represents comprehensively cultivars characteristics of thermal requirements and photoperiod sensitivity. GDD during a development unit is the sum of daily thermal time (DTT) during the period.

$$GDD = \sum_{i=td}^{md} DTT_i \quad (1)$$

$$DTT_i = \begin{cases} 0 & \text{for } T_{\max} \leq T_{base} \text{ or } T_{\min} \geq T_{high} \\ \frac{\sum_{h=1}^{24} (T_{he} - T_{base})}{24} & \text{for } T_{\max} > T_{opt} \text{ or } T_{\min} < T_{base} \\ \frac{T_{\max} + T_{\min}}{2} - T_{base} & \text{for others} \end{cases}, (2)$$

107 where DTT_i is daily thermal time at day i . td is transplanting date, md is maturity date.

108 $T_{\min}$ and $T_{\max}$ is the daily minimum and maximum temperatures, respectively; T_{base} is

109 base temperature, T_{high} is critical high temperature and T_{opt} is optimum temperature for

110 rice development. T_{he} is hourly effective temperature in h hour in a day, it was

111 calculated by $T_{\min}$ and $T_{\max}$ as follows:

$$T_h = \frac{T_{\min} + T_{\max}}{2} + \frac{T_{\max} - T_{\min}}{2} \cdot \sin(3.14/12 \cdot h) \quad (3)$$

$$T_{he} = \begin{cases} T_{base} & \text{for } T_h < T_{base} \\ T_{opt} - (T_h - T_{opt}) & \text{for } T_h > T_{opt} \\ T_h & \text{for others} \end{cases}, (4)$$

112 where T_h is hourly temperature.

113 HDD from beginning of heading to end of flowering stage was calculated by

114 equations (5-7):

$$HDD = \sum_{i=bh}^{ef} HDD_i \quad (5)$$

$$HDD_i = \frac{1}{24} \sum_{h=1}^{24} HDD_h \quad (6)$$

$$HDD_h = \max(0, T_h - 35) \quad (7)$$

115 where HDD_i is the high temperature degree days at day i . bh is the beginning date of

116 heading stage of rice, ef is the ending date of flowering stage of rice. HDD_h is the high

temperature degree day at hour h . The threshold of high temperature was defined to be 35 because various experimental and observed evidences had indicated that the occurrence of the floret sterility can be induced by air temperature over 35°C at flowering (Satake and Yoshida, 1978; Horie et al., 1996; Matsui et al., 1997a, 1997b).

CDD between rupturing to flowering stage was calculated by equations (8-10):

$$CDD = \sum_{i=br}^{ef} CDD_i \quad (8)$$

$$CDD_i = \frac{1}{24} \sum_{h=1}^{24} CDD_h \quad (9)$$

$$CDD_h = \max(0, 20 - T_h) \quad (10)$$

where CDD_i is the cold degree days at day i . Where br is the beginning date of rupturing stage of rice. CDD_h is the cold degree day at hour h . The threshold of low temperature was defined to be 20 °C (Horie et al., 1996; Sun and Huang, 2011).

2.4. Correlation and trend analyses

Across the stations for early rice, late rice, single rice (I), and single rice (II), the time trends in GDD, HDD, CDD and SRD were determined using a linear regression model. The anomaly of yield, HDD and CDD during 1981-2009 at each station was calculated as de-trended yield, HDD and CDD, respectively. The correlations between GDD, HDD, CDD and SRD, between HDD, heat stress frequency and yield, between CDD, cold stress frequency and yield, were determined using Pearson correlation analyses. Statistical significance of the correlation and trend was tested using the two-tailed t-test method.

2.5. Regression analysis

Panel regression analysis had been indicated to be more suitable for climate change impacts studies (Lobell and Burke, 2010). For early rice, late rice, single rice (I) and single rice (II), yields and weather data at the respective stations were combined into a panel dataset, and then a panel regression model was conducted. We run a Hausman test to decide whether the fixed or random effects model should be used. The fixed effects model was applied since the Hausman test was significant ($p < 0.05$), nevertheless the random effects model was also applied for comparison (Table S1). The Huber-White robust standard errors were calculated, which showed that the error term in the regression model was identically and independently distributed. As Welch et al. (2010), we used multiple regression as following model:

$$Y_{nt} = c_n + \theta_{nt} + \beta w_{nt} + u_{nt} \quad , \quad (11)$$

where Y_{nt} is the observed yield at station n in year t . c_n is a station-level fixed effect, θ_{nt} is a station-specific year fixed effect. w_{nt} is an $N \times K$ matrix of weather variables, where N is the number of observations across stations and years and K is the number of variables. β is a $K \times 1$ vector of parameters that gives the impacts of weather variables including GDD, HDD, CDD and SRD, which is the sensitivity of yield change to the weather variables. u_{nt} is a random error term that represents the impacts of factors other than weather on yield. The sensitivity of yield change to GDD, HDD, CDD and SRD was represented by the estimates of model coefficients β , divided by mean observed yields across the stations for each rice cropping type during 1981–2009 and

expressed as a percentage:

$$\frac{\beta}{Yield_{jo}} \times 100\% \quad , \quad (12)$$

where $Yield_{jo}$ is the mean of observed yields across the stations for each rice cropping type j during 1981-2009.

2.6. Estimating changes in GDD, HDD, CDD and SRD, as well as their impacts on rice yields during 1981-2009

The impact of change in a climate variable (i.e. GDD, HDD, CDD and SRD) on rice yields during 1981–2009 (in percentage) was estimated by multiplying the sensitivity of yield change to the climate variable by change of the climate variable during the period. The latter was estimated by a linear trend. The joint impacts of changes in all the climate variables on crop yields during 1981–2009 (in percentage) were computed by summing the impacts of changes in GDD, HDD, CDD and SRD, based on equation 11.

2.7. Estimating changes in GDD, HDD and CDD and their impacts on rice yields with temperature increase of 1 °C, 2 °C and 3 °C, respectively

To estimate changes in GDD, HDD and CDD and their impacts on rice yields with climate warming, according to the climate change scenarios used in Tao and Zhang (2013a), for each day from 1981-2009 we artificially increased daily T_{min} and T_{max} by 1 °C, 2 °C and 3 °C, and then re-calculated the GDD, HDD and CDD for each station in each year using equations 1-10. Then, changes in GDD, HDD and CDD with

temperature increase of 1°C, 2°C and 3°C were calculated as:

$$WCR_{jm} = \frac{W_{jm} - W_{jo}}{W_{jo}} \times 100\% \quad (13)$$

where WCR_{jm} is the change of a specific weather variable (i.e., GDD, HDD or CDD) for each rice cropping type j (in percentage) with temperature increase of $m^\circ\text{C}$, relative to 1981-2009. W_{jm} is the mean of the specific weather variable for each rice cropping type j with temperature increase of $m^\circ\text{C}$, relative to 1981-2009. W_{jo} is the mean of the specific weather variable each rice cropping type j during 1981-2009.

The impacts on rice yields with temperature increase of 1°C, 2°C and 3°C was calculated as:

$$YCR_{jm} = \beta \times (W_{jm} - W_{jo}) \quad (14)$$

where YCR_{jm} is yield change (in percentage) for each rice cropping type j with temperature increase of $m^\circ\text{C}$. β is the sensitivity of yield (in percentage) to weather variables including GDD, HDD, CDD and SRD, estimated by equation 11.

3. Results

3.1. The indexes HDD and CDD represented well the observed extreme temperature stress on rice

HDD was correlated with heat stress occurrence frequency for early rice (Fig. 2a), late rice (Fig. 2b), single rice (I) (Fig. 2c) and single rice (II) (Fig. 2d). In the year with high heat stress occurrence frequency, the value of HDD was higher than average value and vice versa (Fig. 2). Late rice and single rice (I) suffered more from heat stress than early rice. Rice yield were negatively correlated with HDD (Fig. 3).

Increase in HDD generally reduced rice yield (Fig. 3), although the change of HDD anomaly for early rice was relatively stable (Fig. 3a).

CDD was correlated with cold stress occurrence frequency for early rice (Fig. 4a), late rice (Fig. 4b), single rice (I) (Fig. 4c) and single rice (II) (Fig. 4d). Early rice and late rice suffered more frequent cold stress. Single rice (II) was less affected by cold stress. Yield anomaly was negatively correlated with CDD anomaly for early rice (Fig. 5a), late rice (Fig. 5b), single rice (I) (Fig. 5c) and single rice (II) (Fig. 5d). Increases in CDD generally reduced rice yield (Fig. 5). In the years with higher CDD anomalies, yield anomalies were generally lower.

3.2. Sensitivity of rice yields to changes in GDD, HDD, CDD and SRD

The sensitivity of rice yield to GDD, HDD, CDD and SRD derived from the fixed effects model was presented in Fig. 6. For late rice, single rice (I) and single rice (II), yield was more sensitive to HDD than CDD. But for early rice, yield was more sensitive to CDD than to HDD. For each one-degree day increase in GDD, yield increased by 0.10%, 0.03%, 0.06% and 0.02%, respectively, for early rice, late rice, single rice (I) and single rice (II). For each one degree-day increase in HDD, yield decreased by 0.81%, 0.91%, 0.69% and 0.47%, respectively, for early rice, late rice, single rice (I) and single rice (II). For each one degree-day increase in CDD, yield decreased by 2.05%, 0.04%, 0.34% and 0.01%, respectively, for early rice, late rice, single rice (I) and single rice (II).

Rice yield was highly sensitive to changes in SRD. During rice growing period, for

each 1 MJ /m²/day increase in SRD, yield increased by 2.10%, 2.21%, 6.44% and 4.71% for early rice, late rice, single rice (I) and single rice (II), respectively.

3.3. Changes in GDD, HDD, CDD and SRD and their impacts on rice yields during 1981-2009

During 1981-2009, for early rice, late rice, single rice (I) and single rice (II), GDD increased significantly by 19.48 (p<0.01), 21.51 (p<0.01), 47.20 (p<0.01), 49.10 (p<0.01) degree-days/decade, respectively. HDD increased by 0.06 (p>0.05), 0.12 (p>0.05), 0.17 (p>0.05) and 0.10 (p>0.05) degree days/decade, respectively (Fig. 7). By contrast, CDD decreased by 0.27 (p<0.05), 2.20 (p<0.01), 0.16 (p>0.05), 0.16 (p<0.01) degree-days/decade, respectively (Fig. 7). In particular, CDD decreased significantly for late rice and single rice (II). SRD decreased by 0.16 (p>0.05), 0.02 (p>0.05), 0.50 (p<0.05) and 0.44 (p<0.05) MJ/m²/day/decade for early rice, late rice, single rice (I) and single rice (II), respectively (Fig. 7).

The changes in GDD, HDD, CDD and SRD during 1981-2009 had caused measurable impacts on rice yields (Fig. 8). For early rice, late rice, single rice (I) and single rice (II), increase in GDD during rice growing period increased yield by 5.83%, 1.71%, 8.73% and 3.49%, respectively (Fig. 8); increase in HDD during rice growing period reduced yield by 0.14%, 0.32%, 0.34% and 0.14%, respectively (Fig. 8). Decrease in CDD during rice growing period increased yield by 1.61%, 0.26%, 0.16% and 0.01%, respectively (Fig. 8). Decrease in SRD during rice growing period reduced yield by 0.96%, 0.13%, 9.34% and 6.02%, respectively (Fig. 8). And changes in GDD,

HDD, CDD and SRD jointly increased yield by 6.32% and 1.53% for early rice and late rice, but reduced yield by 0.80% and 2.66% for single rice (I) and single rice (II), respectively (Fig. 8).

3.4. Changes in GDD, HDD and CDD and the impacts on rice yields with temperature increase of 1 °C, 2 °C and 3 °C, respectively

GDD and HDD will increase with temperature increasing. With temperature increase of 1 °C, 2 °C and 3 °C, respectively, GDD will increase by 3.75%, 6.65% and 8.50% for early rice; increase by 1.73%, 1.93% and 1.04%, respectively, for late rice; increase by 0.96%, 1.35%, 0.28%, respectively, for single rice (I). It will increase by 0.01%, however decrease by 1.03% and 3.40%, respectively, for single rice (II) (Fig. 9). HDD will increase by 313.62%, 590.15% and 941.39% respectively, for early rice; increase by 466.36%, 935.59% and 1667.92%, respectively, for late rice; increase by 265.10%, 477.98% and 791.85%, respectively, for single rice (I); increase by 378.2%, 757.67% and 1329.70%, respectively, for single rice (II). With temperature increasing, HDD will increase most for single rice (II) and increase least for single rice (I) (Fig. 9).

By contrast, CDD will decrease with temperature increasing. With temperature increase of 1 °C, 2 °C and 3 °C, CDD will decrease by 33.95%, 57.07% and 77.91%, respectively, for early rice; will decrease by 40.49%, 63.70% and 78.82%, respectively, for late rice; decrease by 56.02%, 83.65% and 94.74%, respectively, for single rice (I); decrease by 62.19%, 89.33% and 97.46%, respectively, for single rice

(II). With temperature increasing, CDD will decrease most for early rice and decrease least for late rice (Fig. 9).

With temperature increase of 1°C, 2°C and 3°C, respectively, increase in GDD will increase yield by 3.87%, 6.96% and 9.12% for early rice (Fig. 10); increase yield by 0.42%, 0.52% and 0.26% for late rice (Fig. 10); increase yield by 1.22%, 1.32% and 0.26% for single rice (I) (Fig. 10). For single rice (II), yield will increase by 0.05% due to increase in GDD with temperature increase of 1°C, however will decrease by 0.38% and 1.27% due to increase in GDD with temperature increase of 2°C and 3°C, respectively (Fig. 10).

With temperature increase of 1°C, 2°C and 3°C, respectively, increase in HDD will reduce yield by 4.43%, 8.30% and 13.50% for early rice; reduce yield by 0.72%, 1.51% and 2.78% for late rice; reduce yield by 2.63%, 5.04% and 8.41% for single rice (I); and reduce yield by 1.29%, 2.63% and 4.63% for single rice (II) (Fig. 10).

With temperature increase of 1°C, 2°C and 3°C, decrease in CDD will increase yield by 0.43%, 0.73% and 0.99% for early rice; increase yield by 0.04%, 0.06% and 0.07% for late rice; increase yield by 0.10%, 0.15% and 0.17% for single rice (I); and increase yield by 0.01%, 0.01% and 0.01% for single rice (II) (Fig.10). In average, with temperature increase by 1, 2 and 3°C, rice yield will increase by 1.39%, 2.11% and 2.09% due to increase in GDD, decrease by 2.27%, 4.37%, 7.32% due to increase in HDD, and increase by 0.14%, 0.23%, 0.31% due to decrease in CDD.

With temperature increase of 1°C, 2°C and 3°C, changes in GDD, HDD and CDD jointly will reduce yield by 0.12%, 0.62% and 3.39% for early rice; jointly reduce

yield by 0.26%, 0.93% and 2.45% for late rice; jointly reduce yield by 1.31%, 3.58% and 7.99% for single rice (I); jointly reduce yield by 1.24%, 3.01% and 5.89% for single rice (II) (Fig.10).

4. Discussion

4.1. Rice yields in southern China increased generally with mean temperature increasing so far

In this study, trial data on rice phenology, agro-meteorological hazards and yields during 1981-2009 at 120 national agro-meteorological experiment stations were used to investigate extreme temperature impacts on rice yields in southern China. The micro-level panel dataset used in the study covers a larger number of experiment stations and a longer time period than any previous micro-level panel study on climate change and rice. The greater scope of our dataset in both spatial and temporal dimensions positions us to estimate the effects of year-to-year weather variation on rice yields more precisely and with less bias than prior studies.

Our result showed that GDD was increased in the past three decades. Some previous studies also suggested that mean temperature during rice growing period fell generally in the optimum temperature range for rice development (Sanchez et al., 2014) in southern China (Welch et al., 2010; Tao et al., 2013a). Increase in mean temperature improved heat resources, providing potential for adopting varieties with longer growth duration (Tao et al., 2013a). As a result, GDD during rice growth period increased significantly, which increased rice yield in southern China. In addition,

increase in mean temperature increase crop photosynthesis rate and biomass accumulations, which contribute to yield increase (Tao et al., 2013a).

Furthermore, cold stress reduced notably with climate warming, which increased rice yield, particularly for late rice. The finding is supported by some previous studies. For example, previous studies found that climate change in the past several decades reduced cold stress on rice in southern China (Sun and Huang, 2011; Tao et al., 2013b; Zhang et al., 2014).

In addition, SRD is also an important factor which may affect on rice production substantially. In our studies, SRD during rice growth period decreased in the past three decades, which reduced rice yield notably, particularly for early rice, single rice (I) and single rice (II). The result is supported by some previous studies, which found that SRD and mean temperature during rice growth period were positively related to rice yield in southern China (Tao et al., 2008; 2013a; Zhang et al., 2010; Shuai et al., 2013).

4.2. Rice yields in southern China face increasing risk of extreme high temperature stress with climate warming

Here, based on more detailed data and robust indexes (i.e. HDD and CDD), our analyses accounted for the adaptations such as shifts of sowing date, phenological dynamics and cultivars and quantified the extreme temperature more precisely. The results indicated that climate change did increase the frequency and severity of extreme high temperature events in the past decades in southern China, and rice yield

was reduced by extreme high temperature stress by up to 0.18%, even accounting for the automatic adaptations.

The impacts mechanisms of extreme high temperature stress have been extensively investigated. Rice is extremely sensitive to high temperature at anthesis stage (Yoshida et al., 1981; Matsui et al., 1997a,b; Jagadish et al., 2007). High temperature stress can induce sterility if the sensitive physiological processes, such as anther dehiscence, pollination, pollen germination on the stigma, pollen tube growth or the early events of fertilization, are affected (Yoshida et al., 1981; Matsui et al., 1997a,b; Jagadish et al., 2007).

The final impacts of climate change on rice yield depend on the joint impacts of all the climatic variables, although the positive impacts of increase in GDD and the negative impacts of decrease in SRD played dominant roles so far. However, with projected climate warming in future, HDD is projected to increase substantially and play more important roles, finally undermine the positive impacts of changes in GDD and CDD, the probability of rice yield reduction is increasing with climate change. With temperature increase of 3°C, yield will decrease for early rice, late rice, single rice (I) and single rice (II) in the study region. The results are consistent with previous studies using crop simulation models (Tao and Zhang, 2013). Adaptation strategies, such as shifts of planting dates to prevent from heat stress and developing heat-tolerant varieties, should be developed.

5. Conclusions

Long-term trial data on crop phenology and yield provide us the unique opportunity to investigate the impacts of extreme weather on rice yields more precisely and in a setting with automatic adaptations. During 1981-2009, GDD and HDD during early rice and late rice growth period increased significantly. CDD decreased significantly during growing period of late rice. Rice yield was generally more sensitive to HDD than to CDD. The positive impacts of increase in GDD and the negative impacts of decrease in SRD played dominant roles in determining overall climate impacts on yield in the past three decades. However, with climate warming, the positive impacts of increase in GDD and decrease in CDD will be offset by increase in HDD, resulting in overall negative impacts of climate change on yield. Our findings highlight the risk of extreme high temperature stress on rice yield and the necessity of developing integrated adaption strategies to cope with extreme high temperature stress.

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Figure captions:

Fig. 1. The study region, rice cropping system and the locations of the rice agricultural meteorological experimental stations used in this study

Fig. 2. Time series of heat stress occurrence frequency based on the observed records and HDD for early rice (a), late rice (b), single rice (I) (c) and single rice (II) (d)

Fig. 3. Time series of HDD anomaly and yield anomaly for early rice (a), late rice (b), single rice (I) (c) and single rice (II) (d).

Fig. 4. Time series of cold stress occurrence frequency based on the observed records and CDD for early rice (a), late rice (b), single rice (I) (c) and single rice (II) (d).

Fig. 5. Time series of CDD anomaly and yield anomaly for early rice (a), late rice (b), single rice (I) (c) and single rice (II) (d)

Fig. 6. Sensitivity of rice yield to GDD, HDD, CDD and SRD for early rice, late rice, single rice (I) and single rice (II), respectively

Fig. 7. Trends in GDD (degree-days/decade), HDD (degree-days/decade), CDD (degree-days/decade) and SRD ($\text{MJ}/\text{m}^2/\text{day}/\text{decade}$) during 1981-2009 for early rice, late rice, single rice (I) and single rice (II) , respectively

Fig. 8. Impacts of changes in GDD, HDD, CDD and SRD on rice yields during 1981-2009 for early rice, late rice, single rice (I) and single rice (II) , respectively

Fig. 9. Changes of GDD, HDD and CDD with temperature increase of 1°C , 2°C and 3°C , respectively, for early rice, late rice, single rice (I) and single rice (II)

Fig. 10. Impacts of changes in GDD, HDD and CDD on yield with temperature increase of 1°C , 2°C and 3°C , respectively, for early rice, late rice, single rice (I)

481 and single rice (II)

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