Spatial and Temporal Characteristics of Post-heading Heat Stress and its Yield Impact on Rice in South China

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Summary: Based on the analysis of observed climate and phenology data from 228 stations in South China during 1981-2010, the spatio-temporal variation of post-heading heat stress was investigated among two single-season rice sub-regions in the northern Middle and Lower Reaches of Yangtze River (S-NMLYtz) and Southwest Plateau (S-SWP), and two double-season early rice sub-regions in the southern Middle and Lower Reaches of Yangtze River (DE-SMLYtz) and Southern China (DE-SC). Post-heading heat stress was more severe in DE-SMLYtz, west S-NMLYtz and east S-SWP than elsewhere, because of rice exposure to the hot season during post-heading stage. The spatial variation of post-heading heat stress was greater in single-season rice region than in double-season early rice region due to the greater spatial variation of heading and maturity dates. Post-heading heat stress increased from 1981 to 2010 in most areas, with significant increases in the east of double-season early rice region and west S-SWP. Phenology shift during 1981-2010 mitigated the increasing trends of heat stress in most areas, but not in west S-SWP. Post-heading heat stress played a dominated role in the reduction of rice yield in South China. Grain yield was more sensitive to post-heading heat stress in double-season early rice region than that in single-season rice region. Rice yield decreased by 1.5%, 6.2%, 9.7% and 4.6% in S-NMLYtz, S-SWP, DE-SMLYtz and DE-SC, respectively, because of post-heading heat stress during 1981-2010, although there were some uncertainties. Given the current level and potential increase of post-heading heat stress in South China, the specific adaptation or mitigation strategies are necessary for different sub-regions to stabilize rice production under heat stress.

Key words: Heat stress, Spatio-temporal variation, Phenology shift, Grain yield, Rice, South China

1. Introduction

With the intensification of climate change, short episodes of extreme high temperature events become more and more frequent around the world [1-3]. High temperature above the tolerance threshold of crop growth can cause heat stress, which has greatly negative impacts on grain yield and quality [4-6]. Nevertheless, heat stress in general has not been seriously addressed when estimating the effects of climate warming on agricultural production [7-9]. Recent studies indicated that frequent heat stress events with a warming climate will pose great risks on crop yield stability [10-12].

Rice is a staple food for more than half of the world's population. As the largest rice producer in the world, China contributes about 28% of the world rice production with 18.5% of the planting area [13]. Heat stress, particularly during the crop reproductive period, could result in dramatic yield reductions [5, 14, 15]. In addition, heat stress occurs during crop growth period concomitantly with a complex spatio-temporal variation [16]. Hence, analyzing the spatio-temporal variation of post-heading heat stress and its impact on rice grain yield is important to ensure food security. Rice phenology varies with different eco-regions and different climatic conditions across China. Previous studies on the analysis of heat stress generally used a fixed phenological date among different eco-sites or growth seasons [17, 18], which probably resulted in the underestimation or overestimation of spatial and temporal variations.

The objectives in this study are: (1) to investigate the spatio-temporal characteristics of post-heading heat stress by calculating heat stress indices from 228 stations during 1981-2010 in the major rice planting regions of South China; (2) to analyze the effects of phenology shift on the trends of post-heading heat stress in rice among different sub-regions; (3) to determine the effect of post-heading heat stress on rice grain yield in South China during 1981-2010.

2. Materials and methods

1) Sites and data selection

The study areas included 14 major rice production provinces or municipalities in South China as proposed by the Ministry of Agriculture in China in 2009 (http://www.agri.gov.cn), and four rice planting sub-regions were classified across the whole study region, including two single-season rice planting regions, the northern Middle and Lower Reaches of Yangtze River sub-region (S-NMLYtz) and the Southwest Plateau sub-region (S-SWP), and two double-season early rice planting regions, the southern Middle and Lower Reaches of Yangtze River sub-region (DE-SMLYtz) and the Southern China sub-region (DE-SC) (Fig. 1). 228 weather stations including 105 single-season rice planting sites and 123 double-season early rice planting sites were selected to calculate heat stress indices (Fig. 1). Historical daily maximum temperature data, rice phenological dates and grain yield data at each weather station in the study region from 1981 to 2010 were obtained from the Chinese Meteorological Administration (CMA).

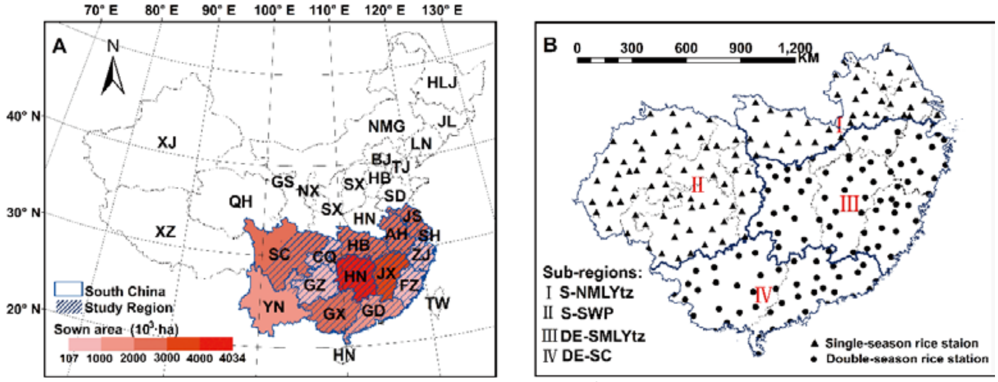

Fig. 1. Study region (A) and location of weather stations (B).

(Triangles and dots in Fig. 1B indicate the weather stations in single-season rice region and double-season rice region, respectively. Abbreviations of province or municipality are as follows: JS, Jiangsu; SH, Shanghai; AH, Anhui; HB, Hubei; CQ, Chongqing; SC, Sichuan; ZJ, Zhejiang; JX, Jiangxi; HN, Hunan; GZ, Guizhou; YN, Yunnan; FZ, Fuzhou; GD, Guangdong; GX, Guangxi. Abbreviations of the four sub-regions are as follows: S-NMLYtz, single-season rice sub-region in the northern Middle and Lower Reaches of Yangtze River; S-SWP, single-season rice sub-region in Southwest Plateau; DE-SMLYtz, double-season early rice sub-region in the southern Middle and Lower Reaches of Yangtze River; DE-SC, double-season early rice sub-region in Southern China.)

2) Data analysis

The calculation of heat stress indices was summarized in Table 1. The average value of each index at each station during 1981-2010 was determined to show the spatial variation of post-heading heat stress in the study region. In order to detect the general temporal change from 1981 to 2010, annual trends of heat stress indices (Tr) at each station were calculated by fitting the time series of each index over 1981-2010 with linear regression. The difference between annual trends of heat stress indices calculated with the actual phenological dates (Tr) and with the fixed phenological dates (Tr_{mxt}) generally represented the effects of phenology shift on annual trend of heat stress (Tr_{phe}) from 1981 to 2010. The statistical model for grain yield variation in response to temperature variation was preliminarily proposed as Eq. (1):

$$\Delta Y_i = \beta_0 + \beta_1 \Delta GDD_i + \beta_2 \Delta HDD_i + \varepsilon \qquad (1)$$

Table 1. Definition of heat stress indices.

Index	Abbreviation	Unit	Definition
Accumulated days of heat stress	ADHS	d	Number of days when $T_{max} \geqslant T_h$ from heading to maturity
Heat stress intensity	HSI	℃	Average T_{max} in days when $T_{max} \geqslant T_h$ from heading to maturity
Heat degree-days	HDD	℃·d	Accumulated heat degree days from heading to maturity

T_{max}: daily maximum temperature; T_h: the threshold temperature of heat stress.

3. Results

1) Spatial variation of post-heading heat stress in South China

Distinct spatial variation of post-heading heat stress was showed in the study region from 1981 to 2010, based on the observed phenological date of each year at each station (Fig. 2). The spatial variation for the average values during 1981-2010 of each heat stress index indicated that the post-heading heat stress was more serious in the central areas of the study region, including east S-SWP and west S-NMLYtz in single-season rice region and DE-SMLYtz in double-season rice region, than in the other areas. Moreover, larger spatial variation of heat stress was observed in the single-season rice region (S-SWP and S-NMLYtz), with obvious east-west spatial difference, than that in the double-season early rice region.

The average value of ADHS after heading during 1981-2010 in east SWP, west S-NMLYtz and DE-SMLYtz could be up to 10.4 days (d), 4.2 d more than that in the other parts of the study region. The average HSI after heading in the central areas of the study region was 36.4℃, 0.9℃ higher than that in the other areas. The average HDD after heading in east S-SWP and DE-SMLYtz was about 14.5℃·d, three times higher than that in S-NMLYtz and DE-SC, and nearly six times the value in west S-SWP. The areas with the most serious heat stress in the single-season rice region and double-season early rice region were Chongqing (CQ) municipality in S-SWP and Zhejiang (ZJ) province in DE-SMLYtz, where the ADHS after heading were up to 11.2 d and 10.6 d, the HSI after heading were up to 36.5℃ and 36.3℃, and the HDD after heading were up to 28.6℃·d and 24.3℃·d on average during 1981-2010 (Fig. 2).

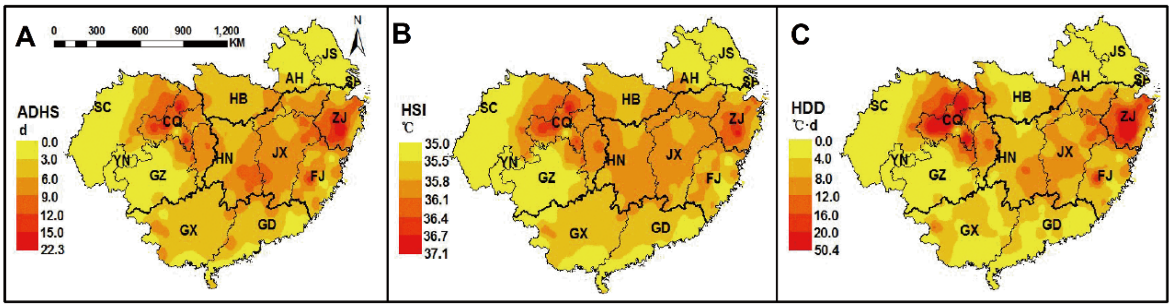

Fig. 2. Spatial variation of post-heading heat stress indices from 1981 to 2010.
(Data above were calculated based on the observed phenological dates of each year at each station. ADHS, accumulated days of heat stress; HSI, heat stress intensity; HDD, heat degree days.)

2) Temporal trends of post-heading heat stress from 1981 to 2010

From 1981 to 2010, post-heading heat stress in rice increased in the study region except for some areas in the northeast (Fig. 3). The post-heading heat stress decreased in east S-NMLYtz from 1981 to 2010, including Jiangsu (JS) province and most northern areas of Anhui (AH) province, and the average reduction for ADHS in east S-NMLYtz was about 0.06 d·y^{-1}, and for HDD was 0.10℃·d·y^{-1}.

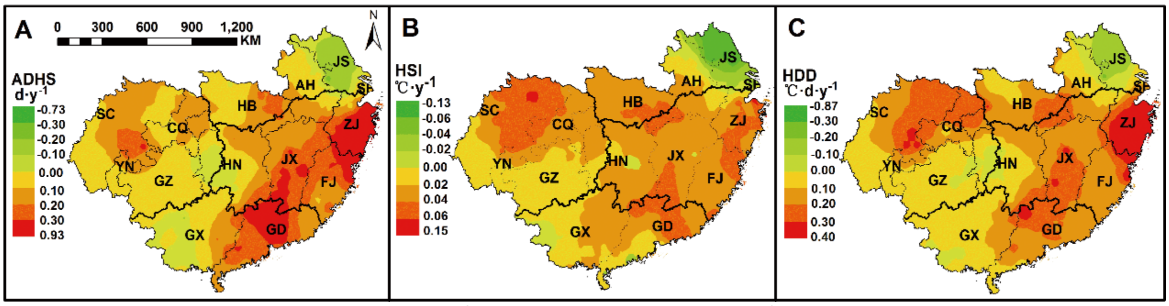

Fig. 3. Temporal trends of post-heading heat stress indices from 1981 to 2010.
(ADHS, accumulated days of heat stress; HSI, heat stress intensity; HDD, heat degree days.)

Nevertheless, there was an obvious increase for post-heading heat stress in the east of double-season early rice region and in west S-SWP (most in northwest Sichuan province) of single-season rice region. This suggested that despite generally being a cooler area (annual average temperature during 1981-2010 was about 10.8℃), west S-SWP had an increasing occurrence for post-heading heat stress. ADHS showed an uptrend of 0.12 d·y^{-1} in the east of the double-season early rice region, and of 0.05 d·y^{-1} in west S-SWP. The increasing trends of HSI in the east of the double-season early rice region and in west S-SWP were 0.042℃·y^{-1}and 0.040℃·y^{-1}, respectively. Trends for HDD were more than 0.2℃·d·y^{-1} both in west S-SWP and in the east of double-season early rice region.

3) Effects of phenology shift on temporal trends of heat stress indices during 1981-2010

Phenology shift affected the temporal trends of post-heading heat stress obviously in the whole study region from 1981 to 2010, with generally similar trends among ADHS, HSI and HDD (Fig. 4). Combined with the findings from Figs. 3 and 4, phenology shift from 1981 to 2010 mitigated the increasing trends of post-heading heat stress in most central areas of South China (at 83.2% stations), while accelerated the increasing trends of post-heading heat stress in west S-SWP and Fujian (FJ) province of southeast DE-SMLYtz. In particular, the decreasing trend of post-heading heat stress was observed in east S-NMLYtz (mostly in Jiangsu (JS) province) (Fig. 3), and phenology shift during 1981-2010 continually accelerated this decreasing trend (Fig. 4).

Because HDD was the comprehensive index that evaluated both heat stress duration and intensity, Table 2 analyzed the effects of phenology shift on temporal trends of post-heading heat stress using HDD index at different sub-region scales. Owing to phenology shift, the increasing trends of post-heading heat stress decreased significantly in S-NMLYtz (from 0.042℃·d·y^{-1} to 0.031℃·d·y^{-1}), DE-SMLYtz (from 0.590℃·d·y^{-1} to 0.323℃·d·y^{-1}) and DE-SC (from 0.249℃·d·y^{-1} to 0.178℃·d·y^{-1}), while did not mitigate in S-SWP ($p=0.842$). Overall, the effects of phenology shift on the temporal trend of post-heading heat stress were significant in the whole study region, with higher significant level in double-season early rice region.

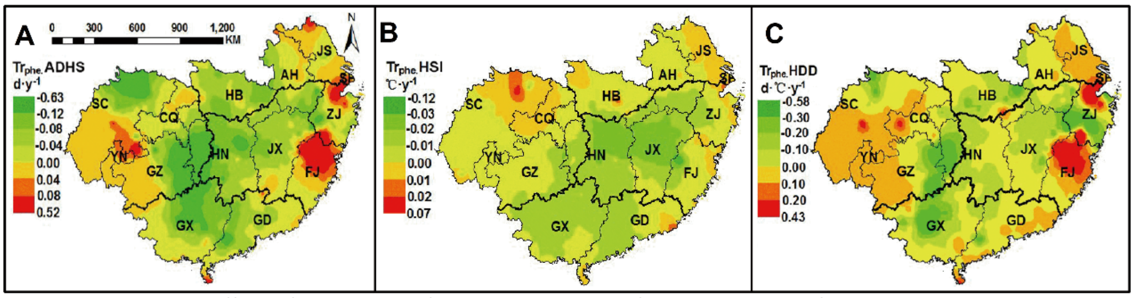

Fig. 4. Effects of phenology shift on temporal trends of heat stress indices from 1981 to 2010.
(ADHS, accumulated days of heat stress; HSI, heat stress intensity; HDD, heat degree days.)

Table 2. The paired t-test on temporal trends of heat degree days (HDD) driven by different influencing factors in each sub-region.

Regions	Average trends of HDD driven by phenology shift and by variations of maximum temperature Tr.ave ($℃ \cdot d \cdot y^{-1}$)	Average trends of HDD driven by variations of maximum temperature Tr_{mxt}.ave ($℃ \cdot d \cdot y^{-1}$)	Average trends of HDD driven by phenology shift Tr_{phe}.ave ($℃ \cdot d \cdot y^{-1}$)	P-value
S-NMLYtz	0.031	0.042	-0.011	0.000^{**}
S-SWP	0.245	0.110	0.135	0.842
DE-SMLYtz	0.323	0.590	-0.267	0.046^{*}
DE-SC	0.178	0.249	-0.071	0.000^{**}
SR	0.006	0.102	-0.096	0.379
DER	0.276	0.455	-0.179	0.010^{**}
South China	0.175	0.311	-0.136	0.018^{*}

4) The impact of heat stress on rice grain yield

Table 3 was the partial correlation analysis on the relationship of ΔHDD and ΔGDD with ΔY. Significant negative correlations were observed between ΔY and ΔHDD among four sub-regions in South China, suggesting obvious grain yield loss due to the increase of post-heading heat stress from 1981 to 2010. The variation of post-heading GDD only affected yield variation in S-SWP, and the significance level of the correlation between ΔY and ΔGDD ($p=0.029$) was less than that between ΔY and ΔHDD ($p=0.000$). These results indicated that post-heading heat stress was more important for rice grain yield variation among the four sub-regions during 1981-2010, as compared with effective accumulated temperature.

Table 3. Partial correlation analysis on the relationship of ΔHDD and ΔGDDwith ΔY in each sub-region of South China.

Sub-region	Temperature variable	Partial correlation oefficient	P value
S-NMLYtz	ΔHDD	-0.219	0.026^{*}
	ΔGDD	0.089	0.415
S-SWP	ΔHDD	-0.296	0.000^{**}
	ΔGDD	0.124	0.029^{*}
DE-SMLYtz	ΔHDD	-0.275	0.023^{**}
	ΔGDD	-0.106	0.120
DE-SC	ΔHDD	-0.453	0.000^{**}
	ΔGDD	-0.028	0.481

Yield variation due to the increasing temperature was estimated both by considering GDD and HDD (type Ⅰ), and by considering only HDD (type Ⅱ) during the post-heading stage. Table 4 showed that there was no obvious improvement for determination coefficients (R^2) of the statistical model of type Ⅰ in S-NMLYtz, DE-SMLYtz and DE-SC, as compared with that of type Ⅱ, suggesting yield variation in these sub-regions was mainly affected by post-heading heat stress. However, yield variation in S-SWP was affected both by heat stress and by effective accumulated temperature during post-heading stage, as indicated by the change of R^2 between the two types of statistical models. These results were consistent with the partial correlation analysis between rice grain yield and temperature variables (Table 3). With the selected statistical model at different sub-regions, the sensitivities of grain yield to post-heading HDD (yield change for each 1℃•d increase of HDD) in rice were -1.2%, -0.9% and -1.1% in S-NMLYtz, DE-SMLYtz and DE-SC, respectively, as indicated by $\beta 2$. In S-SWP, the sensitivities of grain yield were -0.8% and 0.09% with each 1℃•d increase of HDD and GDD during post-heading stage, respectively. Fig. 5 showed that there were differences in the sensitivity of grain yield to temperature variables among different stations of each sub-region. Although there were some uncertainties at different stations, post-heading heat stress generally decreased rice grain yield in each sub-region and in the two planting systems (single-season rice and double season early rice) of South China.

Table 4. Regression coefficients and determination coefficients (R^2) of statistical model for grain yield in response to temperature variables (per unit).

Sub-regions	Considering HDD and GDD (type Ⅰ)				Considering only HDD (typeⅡ)		
	β_0	β_1	β_2	R^2	β_0	β_2	R^2
S-NMLYtz	0.011	0.0005	-0.011^{**}	0.138	**0.013**	**-0.012^{**}**	**0.134**
S-SWP	**0.024**	**0.0009^{*}**	**-0.008^{**}**	**0.173**	0.021	-0.007^{**}	0.112
DE-SMLYtz	0.005	-0.0007	-0.009^{**}	0.215	**0.004**	**-0.009^{**}**	**0.208**
DE-SC	0.007	-0.0006	-0.010^{**}	0.295	**0.006**	**-0.011^{**}**	**0.290**

The total contribution of post-heading heat stress to rice yield variation at each sub-region from 1981 to 2010 was showed in Fig. 6. From 1981 to 2010, post-heading heat stress generally decreased rice grain yield by 1.5%, 6.2%, 9.7% and 4.6% in S-NMLYtz, S-SWP, DE-SMLYtz and DE-SC, respectively. Rice production in double-season early rice region (S-NMLYtz and S-SWP) was more affected by post-heading heat stress due to climate warming than that in single-season rice region (DE-SMLYtz and DE-SC). Total yield losses from 1981 to 2010 were 3.9% and 7.4% with the increase of post-heading heat stress in single-season rice region and double-season early rice region, respectively.

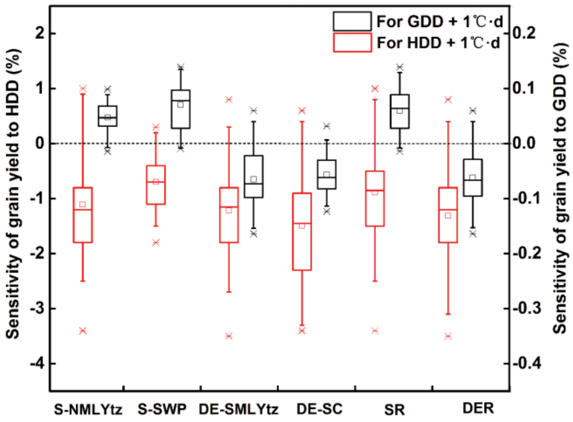

Fig. 5. Boxplots of the sensitivities of grain yield to post-heading HDD and GDD in different sub-regions. Sensitivities of grain yield were estimated due to the increase of per-unit HDD and per-unit GDD during post-heading stage in rice at different stations of each sub-region. The upper and lower boundaries of the box indicate the 75th and 25th percentiles, respectively. The above and below whiskers indicate the 95th and 5th percentiles, respectively. The line within the box marks the median value and the pane in the box indicates the mean value.

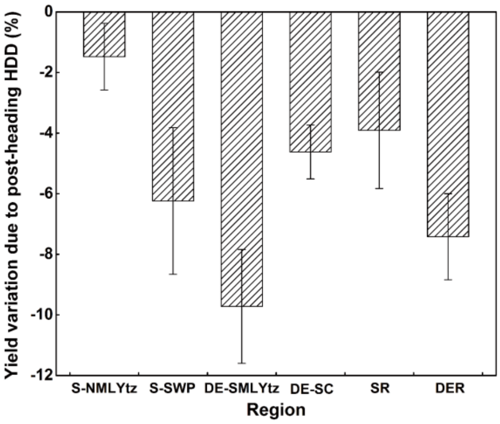

Fig. 6. Contribution of post-heading heat stress to yield variation (%) during 1981-2010 in different sub-regions. Whiskers show the 95% confidence interval.

4. Conclusions

Large spatial and temporal variations of post-heading heat stress in rice were observed in South China, with differences among four sub-regions. The spatial variation of heat stress was greater in the single-season rice region than the double-season early rice region. The most serious heat stress occurred in the central areas of South China according to the average values of heat stress indices from 1981 to 2010. Post-heading heat stress increased in most rice planting regions of South China during 1981-2010, with the higher uptrends in the east of double-season early rice region and west Sichuan (SC) province. Phenology shift mitigated the increasing trend of post-heading heat stress in most central areas of South China during 1981-2010. Post-heading heat stress played the dominated role on rice yield variation among four sub-regions in South China, as compared with the effective accumulated temperature during post-heading growth season. Despite some uncertainties, post-heading heat stress averagely decreased rice production by 3.9% and 7.4% in single-season rice region and double-season early rice region, respectively. Rice production across South China was affected by the post-heading heat stress since 1980s, and the specific adaptation or mitigation strategies are needed for different sub-regions to ensure food security under climate change.

Acknowledgement

This work was supported by the National High-Tech Research and Development Program of China (2013AA100404), and the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD).

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