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Abstract: Heat stress will restrict rice yield in the middle and lower reaches of the Yangtze River. An understanding of the meteorological conditions of heat stress of rice production is important for improving the accuracy of the phenology simulation. Based on the observations of phenology and heat stress of rice agrometeorological stations in this region, as well as meteorological observations and future scenarios, this study analyzed the spatiotemporal change of heat stress and its impacts on rice growth in this region from 1990 to 2009. The results showed that the heat stress frequency of early rice increased in this region from 2000 to 2009, and that of late rice and single-season rice decreased. Moreover, rice phenology will advance under heat stress conditions. The spatiotemporal consistency of the observations and the meteorological index of heat stress shows that the change in heat stress is attributed to climate changes and extreme meteorological events. Under future climate scenarios, it is found that the frequency of heat stress will increase, which will have a serious impact on rice production. The results suggest that positive and effective measures should be taken to adapt to climate change for rice production.

Keywords: middle and lower reaches of Yangtze River; rice; climate change; heat stress

1. Introduction

In recent years, the global climate has shown a significant change characterized by warming. The global surface temperature increased by 0.69~1.08 °C from 1901 to 2012 [1]. Heat stress caused by climate warming is a risk for global food production for the regions where heat stress happens frequently [2–4], such as East Asia, Southeast Asia, and South Asia.

Rice is one of the most important main food crops in the world [5,6]. China accounts for a quarter of the world's planting area [7,8]. And rice production in China has reached one-third of the world's total rice production [9]. Rice is sensitive to temperature changes [10,11]. Heat stress is the main climate variable which has substantial impact on the rice production [12]. Studies have shown that when the temperature rises by 1 °C, the rice production is reduced by 10% [13]. As the frequency of extreme heat events increases, it will lead to an obvious decrease in rice production [14]. The impact of heat stress on rice yield based on a meta-analysis was studied. This analysis found that the mean yield of rice was reduced by 39.6% due to heat stress worldwide [15].

The responses of rice growth to heat stress is different for different developmental stages. The sensitivity of rice growth for heat stress during different rice growing periods was in the order of heading stage and flowering stage > young panicle development stage > filling stage [16]. Heat stress occurring in the reproductive growing period will cause a short pollen germination rate and decreased pollen viability, which result in rice grain spikelet sterility [17]. If it occurs in the young panicle development stage, it will inhibit the differentiation and degeneration of the spikelet. Heat stress during the grain-filling period resulted in faster translocation of photosynthates, it will shorten the length of the grain-filling period, reduce grain weight and imperfect grains. Warming stress from heading to maturity will cause



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Copyright: © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). spikelet sterility [18,19]. In the vegetative growing period of rice, heat stress will limit photosynthesis and reduce leaf area and tiller [20]. In addition, the reproductive growing period of rice is sensitive to heat stress, which leads to a decrease in leaf area, plant height, and harvest index and hinders the development of reproductive organs [21]. During the grain-filling period, the total grain-filling duration of rice is shortened by 21.3–37.1% when heat stress happens [20]. Studies have shown that heat stress (35 °C) occurs in the early 72 h of seed development, and the development of endosperm and embryo will be damaged [22], which seriously affects the development of rice.

Heat stress often occurs in the Yangtze River Basin in China [3,23]. This region is an important rice planting areas in China. Because this area belongs to the transition zone of subtropical and warm temperate climate, the regional climate environment is complex, and disastrous weather is prone to occur. Due to global warming, heat, heat waves, and other events, the frequency of heat stress will increase in this region. It is of great significance to study the impact of heat stress on rice growth, which is beneficial to ensure food security in the future in China.

The study aims to explore the spatiotemporal change of heat indices from 1981 to 2009, as proxy of thermal damage to rice production in China by using observations from agrometeorological stations and to project the changes of heat damages under future climate scenarios.

2. Materials and Methods

2.1. Data

The study area is the middle and lower reaches of the Yangtze River (Figure 1). The details of the agrometeorological stations in the study area were shown in Table 1. Data of rice heat stress from 1991 to 2009 were obtained. These data were maintained by the China Meteorological Administration (CMA). Daily weather data were obtained from the Chin Meteorological Administration (CMA). The future climate scenarios were constructed from the Regional Integrated Environmental Model (RIEMS) [24–26].



Figure 1. Agrometeorological stations in study area.

Agrometeorological Stations	Longitude	Latitude	Annual Mean Precipitation (mm)	Annual Mean of Daily Average Temperature (°C)	Annual Mean of Daily Maximum Temperature (°C)	Annual Mean of Daily Minimum Temperature (°C)
Nanxian	112.40	29.36	336.87	18.15	21.25	14.21
Changde	111.68	29.05	368.70	17.82	21.53	14.32
Huaiyin	119.03	33.60	188.04	15.16	20.00	11.16
Chuxian	118.30	32.30	311.93	16.12	20.56	12.16
Liuan	116.50	31.75	285.85	16.42	20.80	12.64
Tongcheng	116.93	31.05	422.68	16.61	20.64	12.57
Wujin	119.93	31.77	316.33	16.36	20.62	12.97
Jiujiang	116.00	29.73	333.43	18.25	22.19	15.30
Jinhua	119.65	29.11	355.95	18.28	22.59	14.63
Yinxian	121.57	29.87	335.14	17.60	21.75	14.09
Zhangshu	115.55	28.06	277.17	18.59	22.64	15.14
Lishui	119.92	28.45	311.23	19.10	24.07	14.74
Jiaojiang	122.25	28.63	336.23	18.33	22.04	14.81
Nancheng	116.65	27.58	383.53	18.26	22.88	15.04
Guangchang	116.33	26.85	391.61	18.64	23.84	15.01

Table 1. Information of agrometeorological stations in study area.

2.2. Methods

The occurrence frequency of heat events is usually used to represent heat stress for crop studies [19]. The occurrence of heat events is defined by using air temperature measurements according to "The National Agrometeorological Disasters Standard" published by Chinese Meteorological Administration [27]. The daily mean and maximum temperature are the key indicators for counting numbers of occurrence of heat events. If a daily mean temperature above 30 °C for more than three consecutive days or a daily maximum temperature above 35 °C for more than three consecutive days are detected, a heat event is counted. We count numbers of heat events in 1991–2000 and 2000–2009 respectively to explore spatiotemporal change of heat stress. Based on temperature predictions from RIEMS, we also count the occurrence of heat stress events from 2021 to 2040 by using the indices described above. Then the occurrence frequencies in 1981–2000 and 2021–2040 are compared to implicate the possible changes of heat stress in future in study area.

3. Results

3.1. Spatiotemporal Change of Heat Stress

The observations of early rice heat stress from 1990 to 2000 and from 2000 to 2009 showed that the heat stress on rice in Hunan occurred in a few stations, and the frequency of occurrence was the largest. Jiangxi Province has the largest number of stations with heat stress. Comparing the two periods of 1990–2000 and 2000–2009, the frequency of heat stress of early rice increased in most stations (Figure 2).

According to the statistics of heat stress in different growing periods of early rice, it can be found that heat stress of early rice mainly occurs from the tillering stage to the maturity stage. Heat stress occurred mainly at the booting stage, milky ripe stage, and maturity stage at the early rice stations in the study area. From 2000 to 2009, the heat stress of early rice stations in this region mainly occurred in the stage from transplanting to milky ripe, which occurred earlier than that in 1990–2000, and the number of occurrences in each stage increased compared with that in 1990–2000 (Figure 3).



Figure 2. Occurrence frequency of heat stress to early rice in study area from 1991 to 2000 (**a**) and from 2000 to 2009 (**b**) and change of occurrence frequency (**c**).



Figure 3. Occurrence frequency of heat stress in different phenological periods at early rice stations in the study area during 1991–2000 and 2000–2009.

For late rice and single-season rice, the stations with a higher frequency of heat stress were mainly concentrated in Hunan Province. Comparing the two periods of 1990–2000 and 2000–2009, the occurrence frequency of heat stress of late rice and single season decreased at most stations (Figure 4).



Figure 4. Cont.



Figure 4. Occurrence frequency of heat stress to single-season rice and late rice in the study area from 1991 to 2000 (**a**) and from 2000 to 2009 (**b**) and change of occurrence frequency (**c**).

Through the statistics of the heat stress of late rice and single-season rice in different phenology stages, it can be found that the heat stress of late rice and single-season rice in the study area mainly occurred from tillering to maturity from 1990 to 2000. From 2000 to 2009, the heat stress of late rice and single-season rice in the middle and lower reaches of the Yangtze River mainly occurred in the stage from transplanting to milky ripe, which was earlier than that in 1990–2000 (Figure 5).



Figure 5. Occurrence frequency of heat stress in different phenological periods at late rice and single-season rice stations in study area during 1991–2000 and 2000–2009.

3.2. Simulation of Heat Stress

Due to the limited observations of national agrometeorological stations, it is difficult to investigate the occurrence of rice heat stress in the study area. Therefore, based on the standard of rice heat stress and meteorological data issued by the China Meteorological Administration, we counted the occurrence of disasters in the corresponding period (Figure 6).



Figure 6. Cont.



Figure 6. Cont.





From 1991 to 2000, the frequency of heat stress events was less than 20 in the northern of the study area, but more than 20 in the southern part. From 2000 to 2009, the occurrence frequency of heat stress in six provinces in this region was more than 20. The frequency of heat stress events generally shows an increasing trend. The average daily temperature of most stations in summer increased by 0.5 °C in the late period compared with the early period. Except for some stations in eastern China, the standard deviation of mean temperature has increased, which means an increase in extreme heat events (Figure 6).

3.3. Response of Heat Stress of Rice to Climate Change

Under future climate scenarios, we studied the change of rice heat stress in the study area. Based on temperature data of RIEMS, the occurrence frequency and change of heat stress in the study area during 1981–2000 and 2021–2040 were simulated.

From 1981 to 2000, the occurrence of heat stress in this region was generally low. It was 1–3 times in the south and 4–8 times in the north. From 2021 to 2040, the occurrence frequency of heat stress will increase significantly, and the occurrence times of most stations could be more than nine times. Comparing these two time periods, however, the frequency of heat stress increased to varying degrees at all sites from 2021 to 2040 (Figure 7).



Figure 7. Cont.



Figure 7. Simulation result of heat stress in study area during 1981–2000 (**a**) and 2021–2040 (**b**), and change of occurrence frequency (**c**).

From the above results, it can be concluded that the occurrence frequency of heat stress will increase in the future climate scenarios, which will have a serious impact on rice production. The period from June to August is the booting, flowering, and maturing stage of rice, during which the occurrence of extreme heat will seriously weaken the yield of rice. Therefore, the study suggests that the heat at the booting and heading stages of rice can be staggered as far as possible by changing varieties or sowing dates, to improve the yield of rice.

4. Discussion

In this study, the observations of phenology and heat stress of rice agrometeorological stations and the future meteorological predictions are used to investigate the spatiotemporal change of heat stress and its impact on rice growth. It suggested that heat stress occurrence frequency of early rice increased in the study area, whereas that of late rice and single-season rice decreased. Moreover, rice phenology will advance under heat stress. The conclusions are consistent with the previous studies. For example, Liu et al., suggests the heat stress of early rice increased the Yangtze River Basin [17]. They also indicate that heat stress also widely occurs in the most parts of Hubei, Anhui, Jiangsu, Zhejiang, and Hunan. For the growth of early rice, the average occurrence frequency of heat stress was 7.81 days in this region [17]. From 1980 to 2009, heat stress in a single rice planting area had an increase of 1.49 $^{\circ}$ C day, where the increases for early and late rice are about 0.35 $^{\circ}$ C

per day and 1.57 °C per day, respectively [28]. These previous studies indicate that heat stress has substantial impacts on rice growth. Our study further finds that early rice and the late rice had different responses to heat stress. Many previous studies also indicate that relative humidity is an important factor for impacting rice growth [29]. In actuality, changes of relative humidity are highly dependent on temperature changes. Reducing relative humidity under heat conditions is essential for maintaining spikelet fertility [29]. These results suggest that relative humidity is a non-negligible factor for impacting rice growth. In addition, Rehmani et al., suggest that distributions of heat stress are quite different in this region [19]. Our study also finds the different distributions of occurrence frequency of heat stress events in coastline regions and inland regions (Figure 7). This could be caused by the difference of water vapor in these regions. Therefore, it is important to study the complex impacts of relative humidity temperature changes on rice growth. Our results show an increasing trend in heat stress of rice under future scenarios. These results are similar with previous studies. For example, He et al. [14] indicated the occurrence of heat stress of rice will show an increasing trend, and will have an impact on rice yield from the future predictions during 2016–2100. Their results also found that the heat events in the study area will increase by up to 185% and 319% for the RCP 4.5 scenario and the RCP 8.5 scenario, respectively, which will further affect the development of rice [14]. The flowering and maturity of rice will advance under the future climate scenario in the study area [30]. Heat stress will increase with average annual rates of 0.13% and 0.09%, respectively, during 2021–2050 and 2071–2100. Based on all these results, this region will face more heat stress in the future.

In this study, the risk assessment of heat stress is mainly based on statistical methods, meteorological indicators, and climate data under future scenarios. Nowadays, crop models and machine learning methods have also been widely used in meteorological disaster warnings and crop yield assessments. Due to the global climate warming, the response function of development rate to temperature was used to improve the prediction ability of crop models for heading and maturity of double season rice simulations in this region. The heading and maturity simulation accuracy of the improved model increased by 26.2% and 22.9% on average [31]. The improved crop models are also beneficial for improving the prediction skills of warming risks for rice caused by the heat stress. Based on the machine learning method, Li and others have explored the relationship between extreme climate and crop yield which also could be used to monitor extreme heat stress [32]. Therefore, crop models and machine learning methods could be useful tools for accurate prediction of rice yield in the future.

5. Conclusions

In this study, the spatiotemporal change of heat stress and its impacts on rice growth in the study area from 1990 to 2009 were investigated. The occurrence frequency of heat stress events generally shows an increasing trend from 1990 to 2009. For early rice, heat stress occurred mainly at the booting stage, milky ripe stage, and maturity stage at the early rice stations from 1990 to 2000, whereas the stress mainly occurred in the stage from transplanting to milky ripe from 2000 to 2009. For late rice and single rice, the heat stress mainly occurred from the tillering stage to the maturity stage from 1990 to 2000, whereas the heat stress mainly occurred in the stage from transplanting to 2000, whereas the stress mainly occurred in the stage from transplanting to the milky ripe from 2000 to 2009. For late rice and single rice, the heat stress mainly occurred in the stage from transplanting to the milky ripe from 2000 to 2009, whereas the heat stress mainly occurred in the stage from transplanting to the milky ripe from 2000 to 2009, whereas the heat stress frequency of early rice increased in the study area from 2000 to 2009, whereas that of single rice and late rice decreased. From 2021 to 2040, the occurrence frequency of heat stress could increase significantly. The frequency of most stations could increase by more than nine times when compared with the frequency from 1981 to 2000.

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