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Potential rice exposure to heat stress along the Yangtze River in China under RCP8.5 scenario

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ABSTRACT

Along with the global warming, heat events will tend to heighten and should be a matter of concern to rice production. Spatiotemporal changes in single-season rice exposure to heat stress along the Yangtze River during 1971–2100 were evaluated using datasets of single-season rice phenology observation and downscaled daily temperature projections from the 21 models. The results from top two best models which performed well in reproducing daily and seasonal temperatures were compared with that from all 21 models using the ensemble mean method under RCP8.5 scenario. It was found that obvious advances of the date of inflorescence emergence and ripening occurred in most parts of the study region through the period of 2021–2050 and 2071–2100. Duration of exposure to heat stress which was defined as an event of at least 3 successive days with daily mean temperature ≥30 °C or maximum temperature ≥35 °C tended to increase although length of crucial phenology period subjected to heat stress shortened. Mid-eastern Hubei, central Anhui, western Jiangsu, northern Zhejiang and northeastern Hunan were hot spots prone to heat stress. Heat stress for the entire region in the two future periods of 2021–2050 and 2071–2100 increased significantly, with an upward trend of 0.13 and 0.09% d per year for all 21 models and top two best models from 1971 to 2100 respectively. Understanding the potential exposure to heat stress can help decision makers to develop mitigation strategies to ensure rice production security.

1. Introduction

Rice (*Oryza sativa* L.), one of the most important grain crops around the world, is mainly produced in Asia accounting for nearly 90% of the world's production (FAO, 2014). As the largest rice producer, China holds almost 30% and 28% of the global and Asia's production respectively (FAO, 2014). During the past years, rice production has risen rapidly across China (Peng et al., 2009). With population increase in China, more rice should be produced in order to meet the needs of domestic people. About 20% increment by 2030 will be needed in the context of the current stable consumption level (Peng et al., 2009). Nonetheless, inclement weather events have been involved in fluctuation in rice production under climate change. Among them, severe heat damage, induced by global warming, have occurred frequently along the Yangtze River where rice has been cultivated in rain-fed lowland cropping systems (Wassmann et al., 2009; Tian et al., 2010; Huang et al., 2016). Therefore, it is imperative to get better knowledge of the characteristics of rice in response to heat stress under climate change.

Rice can merely be exempted from the effects of hostile environment, especially detrimental heat condition, in consequence of low probability of fleeing the places where they arose (Ruelland and Zachowski, 2010). High temperature beyond the expected range during the growing season, particularly in crucial development stages, inevitably causes irreversible damage to rice development. As observed in mounting research (Matsui et al., 2000; Jagadish et al., 2007, 2008, 2010; Julia and Dingkuhn, 2013), the sterility of rice increased with longer duration of exposure to high temperature during reproductive stage, by affecting anther dehiscence, pollination, and pollen germination. Likewise, due to the exposure to high temperature during the grain filling phase, grain filling rate of rice slowed down and eventually depressed total grain weight (Kobata and Uemuki, 2004; Jagadish et al., 2011).

Global warming, evidenced by greenhouse gas concentrations, is likely to aggravate rice heat stress level. The characteristics of heat stress have received ongoing attentions (Sun and Huang, 2011; Hua et al., 2015; Wang et al., 2016; Huang et al., 2016). Over the recent

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decades, the occurrence of heat stress frequency, as well as intensity, substantially increased (Tao et al., 2013; Zhang et al., 2014; Shi et al., 2015b). A number of studies (Shah et al., 2014; Samol et al., 2015; Shi et al., 2015a) explored rice response to heat stress by simulating the high temperature in controlling experiments and found that obvious acceleration of growth process, enhancement of unfilled grain, and ultimate reduction of yield. Though these controlling experiments were carried out in limited area and might not reproduce the expected increase of temperature in the future, the results could provide thresholds above which rice was affected. Recently, a number of reports (Teixeira et al., 2013; Wang et al., 2014) were addressing the frequency of heat stress based on the future scenarios. It may be generally recognized that climate warming will shorten crop phenology phases and aggravate intensity of heat stress (Moriondo et al., 2011; Kim et al., 2011; Liu et al., 2012). However, whether the rice exposure to heat stress will prolong or shrink in the future, subsequent results from shortened growing season, is still unknown and needs a deeper look.

In this study, we used the latest datasets of rice phenology records and climate projections in the region along the Yangtze River to project future single-season rice exposure to heat stress, and aimed at the following main objectives: (1) To project spatiotemporal changes in the rice phenology process; (2) to investigate the future duration of rice exposure to heat stress at the grid level; (3) to develop a robust heat stress exposure index at the regional level; and (4) to detect potential trend of rice exposure to heat stress under climate change, which can help us develop strategies for adaptation to heat stress.

2. Material and methods

2.1. Study region and data description

The study region is located in the region along the Yangtze River and consists of eastern Sichuan, Chongqing, Hubei, northern Guizhou, northern Hunan, northern Jiangxi, Anhui, Jiangsu, Shanghai and Zhejiang, ranging between 26 °N and 35 °N in latitude and between 103 °E and 122 °E in longitude (Fig. 1).

Single-season rice phenology records of 75 agro-meteorological experimental stations from 1980 to 2015 in the study region were obtained from China Meteorological Administration. The data included the date of seeding, germination, transplanting, tillering, stem elongation, booting, inflorescence emergence, dough, ripening, and final yield.

Daily maximum and minimum near-surface air temperature with a horizontal resolution of 0.25° × 0.25° were downloaded from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) dataset conducted under the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012). This dataset included downscaled projections from the 21 models (Table 1) under two scenarios (RCP4.5 and RCP8.5) (Meinshausen et al., 2011), compiling projections for the period from 2006 to 2100 (except 3 of the 21 models end ed in 2099) as well as the historical experiment from 1950 to 2005. The RCP8.5 scenario was chosen as it represented high emission situation. Then the origin daily maximum temperature (tmax) and minimum temperature (tmin) in Kelvin were converted to equivalent temperatures in degrees Celsius. Daily mean temperature was calculated by averaging daily maximum and daily minimum temperatures in degrees Celsius.

Table 1
21 global climatic models in NEX-GDDP dataset applied in this study (the number in parentheses represents the serial number of the models).

Models (marked number)		
ACCESS1-0 (1)	CSIRO-MK3-6-0 (8)	MIROC-ESM (15)
BCC-CSM1-1 (2)	GFDL-CM3 (9)	MIROC-ESM-CHEM (16)
BNU-ESM (3)	GFDL-ESM2G (10)	MIROC5 (17)
CanESM2 (4)	GFDL-ESM2M (11)	MPI-ESM-LR (18)
CCSM4 (5)	INMCM4 (12)	MPI-ESM-MR (19)
CESM1-BGC (6)	IPSL-CM5A-LR (13)	MRI-CGCM3 (20)
CNRM-CM5 (7)	IPSL-CM5A-MR (14)	NorESM1-M (21)

2.2. Ensemble of projection models

As presented in the previous research referring to climatic models (Xu et al., 2010; Xu et al., 2013), the results of multi-model ensemble mean were more consistent with observation, in contrast with that of individual model which had considerable biases resulting from its uncertainties. Different models showed disagreement on expected changes in particular regions (Giorgi and Francisco, 2000), and certain models reproduced climate processes better than other models. Here, some comparison and assessment of the performance for projection models should be firstly implemented in this study. To address that, the performance of 21 models were evaluated in reproducing the daily maximum/minimum temperature and the seasonal mean maximum/minimum temperature, based on root mean square error (Rmse), standard deviation (Std) and correlation coefficient (Corr) between the simulating temperatures of each model and the actual observation of 141 weather stations across the study region. For daily maximum/minimum temperature at each station, better models with Rmse below 3.0 °C, Std below 1.5 °C and Corr above 0.9 were identified. For

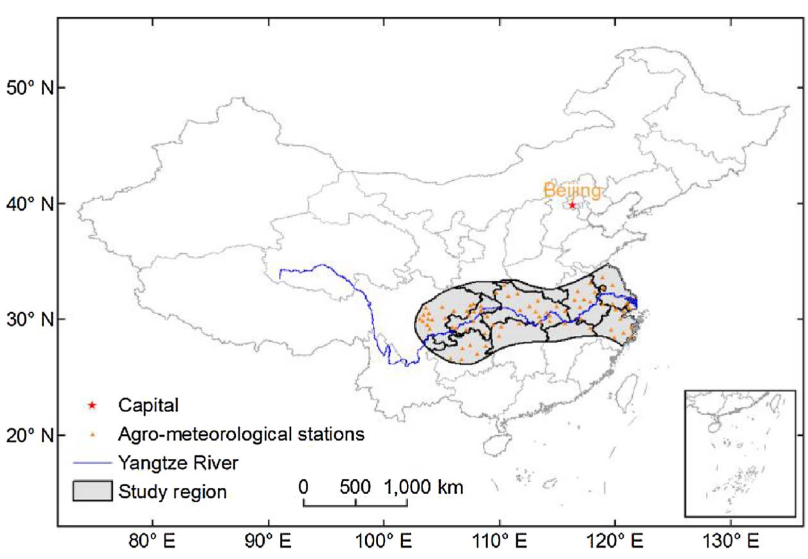

Fig. 1. Location of study region and the distribution of agro-meteorological experimental stations.