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

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ABSTRACT

Extreme temperature impacts on field crop are of key concern and increasingly assessed, however the studies have seldom taken into account the automatic adaptations such as shifts in planting dates, phenological dynamics and cultivars. In this present study, trial data on rice phenology, agro-meteorological hazards and yields during 1981–2009 at 120 national agro-meteorological experiment stations were used. The detailed data provide us a unique opportunity to quantify extreme temperature impacts on rice yield more precisely and in a setting with automatic adaptations. In this study, changes in an accumulated thermal index (growing degree day, GDD), a high temperature stress index (>35 °C high temperature degree day, HDD), and a cold stress index (<20 °C cold degree day, CDD), were firstly investigated. Then, their impacts on rice yield were further quantified by a multivariable analysis. The results showed that in the past three decades, for early rice, late rice and single rice in western part, and single rice in other parts of the middle and lower reaches of Yangtze River, respectively, rice yield increased by 5.83%, 1.71%, 8.73% and 3.49% due to increase in GDD. Rice yield was generally more sensitive to high temperature stress than to cold temperature stress. It decreased by 0.14%, 0.32%, 0.34% and 0.14% due to increase in HDD, by contrast increased by 1.61%, 0.26%, 0.16% and 0.01% due to decrease in CDD, respectively. In addition, decreases in solar radiation reduced rice yield by 0.96%, 0.13%, 9.34% and 6.02%. In the past three decades, the positive impacts of increase in GDD and the negative impacts of decrease in solar radiation played dominant roles in determining 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.

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; Tao et al., 2013a,b; Wassmann et al., 2009; Zhang et al., 2010; Gourdji 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, 1981; Horie et al., 1996; Matsui et al., 1997a, 1997b; Jagadish et al., 2007; Tao et al., 2013a; Tao and Zhang, 2013). 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 experiments (Jagadish et al., 2007), statistical approaches (Welch et al., 2010; Sun and Huang, 2011; Lobell et al., 2011; Tao et al., 2013b; Wang et al., 2014), and improved crop simulation models (Challinor et al., 2005; Tao and Zhang, 2013; Asseng et al., 2015).

Among these studies, the impacts of extreme weather events on field crop in the past few decades are particularly concerned

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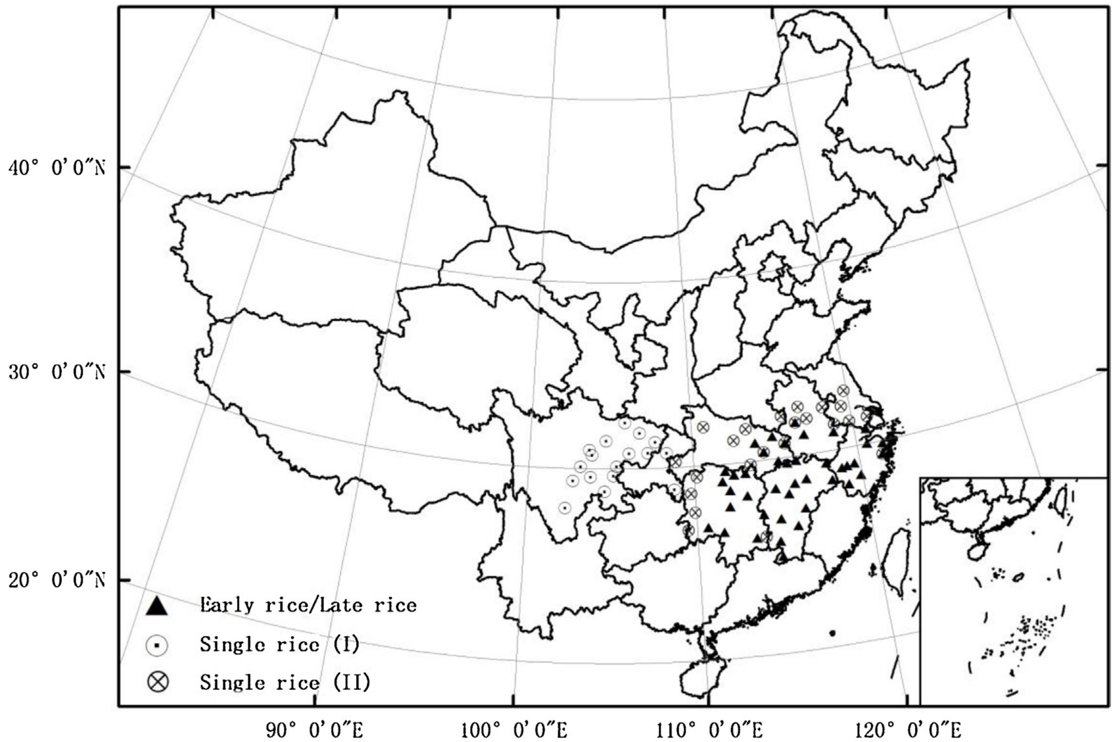

Fig 1. The study region, rice cropping system and the locations of the rice agricultural meteorological experimental stations used in this study.

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

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