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Global warming over 1960–2009 did increase heat stress and reduce cold stress in the major rice-planting areas across China

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ABSTRACT

Increasing extreme temperature events have raised concerns regarding the risk of rice production to extreme temperature stress (ETS). However, across China what places were exposed to higher ETS during rice-growing period and how ETS has changed over the past five decades, remain unclear. Here, we first compared two indexes for characterizing ETS on rice crop, including Duration-based ETS index (DETS) and Growing Degree Days (GDD). Then, based on the better-performing index and an improved dataset of rice phenological records, we comprehensively assessed the spatio-temporal patterns of ETS at county scale in the major rice-planting areas across China during 1960–2009. The results showed that GDD had an advantage over DETS in characterizing ETS, due to fully consideration of both the specific intensity and duration of extreme temperature events. Based on GDD, we found that ETS on rice crops had significantly changed in both space and time over the last five decades. Spatially, single rice in Northeast China (Region I) and late rice in southern China (Region IV) saw high exposure to cold stress, especially during the heading-flowering stage. The hot spots of heat stress were found for single rice in the Yangtze River basin (Region III) (2.25 °C) during the booting stage, and for early rice in Region IV (4.42 °C) during the heading-flowering stage. During 1960–2009, global warming did increase heat stress (0.04 and 0.12 °C year^{-1} for the stages of booting and heading-flowering, respectively) and reduce cold stress (−0.03 and −0.21 °C year^{-1} for the stages of booting and heading-flowering, respectively) in the major rice-planting areas across China. Some particular areas, such as Yunan Province (P4) with increasing cold stress and Zhejiang Province (P13) with increasing heat stress, should be priorities for adaptations to cope with the rising risk of ETS under climate warming.

1. Introduction

China is the world's largest rice producer, contributing almost 30% of the global rice production (FAO, 2010; Tang et al., 2014). However, rice crop in China suffers frequently from extreme temperature events (Sun and Huang, 2011; Wang et al., 2014). In particular, extreme temperatures occurring at crucial times of rice development (e.g., the stages of booting and heading-flowering), even just for a few hours, would drastically reduce final production (Teixeira et al., 2013; Wheeler et al., 2000; Yoshida et al., 1981). Given the increasing frequency and severity of extreme temperature events under ongoing climate change (Gourdji et al., 2013; IPCC, 2007; Porter, 2005), the risk of rice production to extreme temperature stress (ETS) has increasingly been of concern (Porter and Semenov, 2005; Tao et al., 2013; Thakur et al., 2010). Currently, most studies focused on local pattern of rice ETS (He et al., 2009; Liu et al., 2013; Zhang et al., 2011), whereas few studies paid attention to the pattern of ETS across the major rice-planting areas in China. Recently, although Sun and Huang (2011) had described the decadal trends of rice ETS at regional scale, they did not reveal the spatial pattern of ETS across China. Therefore, China urgently needs a reliable assessment of the spatio-temporal pattern of ETS across the major rice-planting areas, particularly at finer spatial scales.

To comprehensively characterize rice exposure to ETS, special attentions should be paid to two critical issues, i.e., the ETS index and rice phenological period. There are different kinds of ETS indexes in China, including qualitative and quantitative indexes. For the former (e.g., GB/T 21985-2008 (2008) and QX/T 101-2009 (2009)), several severity levels (e.g., slight, moderate and severe) could hardly account for the large differences in rice ETS across China, and also have some difficulties for accurate trend analysis. For the latter (e.g., Duration-based ETS index (DETS) (Sun and

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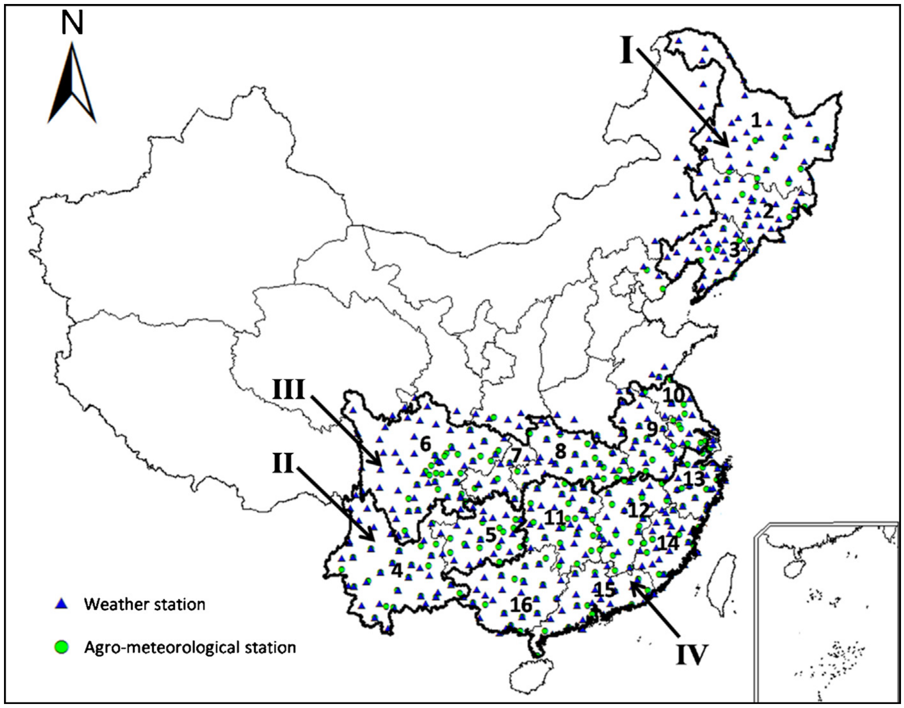

Fig. 1. Spatial distribution of rice cultivation in mainland China: (I) single rice in Northeast China; (II) single rice in the Yunnan-Guizhou Plateau; (III) single rice in the Yangtze River basin; (IV) double rice in southern China. Province codes: (1) Heilongjiang; (2) Jilin; (3) Liaoning; (4) Yunnan; (5) Guizhou; (6) Sichuan; (7) Chongqing; (8) Hubei; (9) Anhui; (10) Jiangsu; (11) Hunan; (12) Jiangxi; (13) Zhejiang; (14) Fujian; (15) Guangdong; (16) Guangxi.

Huang, 2011) and Growing-degree-days (GDD) (Liu et al., 2013; Wang et al., 2014)), there is still a lack of understanding of which one could better characterize the frequency and severity of extreme temperature events across the major rice-planting areas. Besides, rice production is much more sensitive to extreme temperatures in some key growth stages (e.g., the booting and heading-flowering stages), rather than the whole growing season. However, most studies often used crop calendars over a long time scale (monthly, or even the whole growing season) (Liu et al., 2013; Zhang et al., 2014), which could hardly capture the most sensitive episodes. Such lack of a finer time resolution has been one of the biggest challenges in characterizing extreme events (Easterling et al., 2000). Thus, accurate estimation of ETS necessitates a better-performing ETS index and improved rice phenological datasets.

Therefore, in this study, our aims are: (i) to compare the performances of different ETS indexes (i.e., DETS and GDD) and then select a better one to estimate ETS on rice crop; (ii) to assess the spatio-temporal patterns of ETS (1960–2009) at county scale in the major rice-planting areas across China, on the basis of an improved rice phenological dataset from national agro-meteorological stations; (iii) to identify particular areas at higher risk of ETS and suggest some adaptation measures.

2. Method

2.1. Data sources

Our study area included sixteen provinces (or four regions) (Fig. 1), contributing ~96% of the total rice-planting areas in China (Sun and Huang, 2011; Wang et al., 2014; Wang and Zuo, 2010). Rice phenological records from 257 agro-meteorological stations across the major rice-planting areas were obtained from the China Meteorological Administration (CMA) (Fig. 1). These records include the dates of major phenological events, such as sowing, tillering, booting and heading-flowering. Daily temperature data over 1960–2009 were obtained from 411 CMA weather stations across the study area (Fig. 1), including daily mean temperature (T_{mean}), daily minimum temperature (T_{min}) and daily maximum temperature (T_{max}). For each county in the study area, its phenological records and daily temperatures were computed from the nearest agro-meteorological station and weather station, respectively.

2.2. Indexes for characterizing extreme temperature stress: DETS and GDD

DETS (Sun and Huang, 2011) and GDD (Liu et al., 2013; Lobell et al., 2012, 2011; Wang et al., 2014) are two typical quantitative indexes for characterizing ETS on crop growth. In Sun and Huang's study (2011), DETS was used to calculate region-level ETS across the major rice-planting areas. In Liu et al.'s study (2013), GDD was demonstrated to characterize cold stress on rice in Heilongjiang Province (P1 for short, see Fig. 1) better than the national standards (GB/T 21985-2008, 2008) and the meteorological standards (QX/T 101-2009, 2009). Both of DETS and GDD are calculated by adding up ETS of all the extreme temperature events in a given growth stage. However, they define ETS for each event in different ways. For DETS, ETS value (as a percentage) is dependent on the duration of an extreme event, and the ETS-duration relationship is determined from fitting biomass-loss index (as a percentage) against the event duration. Here is an example given by Sun and Huang (2011): "the low-temperature events in a given site occurred twice during the seedling stage. One lasted 3 days (ETS = 1.0) and the other 4 days (ETS = 1.5), the site-specific ETS was then determined to be 2.5 (1.0 + 1.5, see Table 3)". Since Sun and Huang (2011) had defined DETS for different regions in great detail, for briefly, we would only describe the computing process of GDD below.

2.2.1. Threshold of extreme temperature stress based on GDD

Various natural conditions and rice varieties lead to large differences in the thresholds of ETS for different regions in China. When determining the thresholds (Table 1), we mainly consulted national standards (GB/T 21985-2008, 2008), meteorological