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Research Paper

Modeling spatial and temporal variability of the impact of climate change on rice irrigation water requirements in the middle and lower reaches of the Yangtze River, China

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ABSTRACT

Accounting for over 70% of global water withdrawals, irrigation plays a crucial role in the development of agriculture. Irrigation water requirement (*WIRR*) will be influenced by climate change due to the alteration in soil water balances, evapotranspiration, physiology and phenology under global warming. This is particularly true for rice, a high water-consuming crop. Therefore, exploring the impact of climate change on rice *WIRR* is of great significance for the sustainable utilization of water resources and food security. This paper aims to investigate spatially and temporally the responses of rice *WIRR* to climate change in the middle and lower reaches of the Yangtze River (MLRYR), which is one of the most important rice farming districts in China. With the help of the specially developed rice growing period calculation method and water balance model coupled with rice irrigation scheduling, the impacts of climate change on *WIRR* for early rice, late rice and single cropping rice during the historical (1961–2012) and future (2011–2100) periods were evaluated. Meanwhile, to consider the uncertainty from climate models in future projection, four GCMs under RCP2.6, RCP4.5 and RCP8.5 emission scenarios from the 5th Coupled Model Intercomparison Project (CMIP5) were employed as the input of the water balance model. The results indicate the following: (1) The days of growing period (*DGP*) for all three types of rice display shortened trends in historical and most future periods. However, in the middle region of the MLRYR, the *DGP* for early rice and late rice would increase by up to10 days in 2080s under RCP8.5 scenario. (2) Over the past 50 years, the *WIRR* significantly decreased by 1.58 and 2.10 mm yr^{-1} for late rice and single cropping rice, respectively. While for early rice, the *WIRR* only slightly decreased by 0.13 mm yr^{-1}. (3) Projected future *WIRR* would increase for all three types of rice in the whole region under RCP4.5 and RCP8.5 scenarios (up to 100 mm), but decrease for single cropping and late rice in the southeast region (up to 40 mm). The results can provide beneficial reference and comprehensive information to understand the impact of climate change on the agricultural water balance and improve the regional strategy for water resource utilization and agricultural management in the middle and lower reaches of the Yangtze River.

1. Introduction

Continued emissions of greenhouse gases will further unequivocally cause warming and affect all components of the climate system (IPCC, 2013). Within this context, the climate variables such as temperature and precipitation will be undergoing significant changes (Terink et al., 2013; Wang et al., 2013a; Amorim Borges et al., 2014; Wang and Chen, 2014; Okkan, 2015). Under

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most climate change scenarios, global surface temperature change is expected to exceed 1.5 °C at the end of the 21st century (IPCC, 2013). While the precipitation in response to the warming over the 21st century will not be uniform in different regions (IPCC, 2014). Climate change and variability have already affected both natural and social systems (Parmesan and Yohe, 2003; Yu et al., 2006; Huntington, 2006; Wang et al., 2012, 2013b). Agricultural production, one of the most sensitive sectors to climate change, is experiencing significant changes (Piao et al., 2010; Tao and Zhang, 2013; Yang et al., 2013). Irrigation, accounting for 70% of global water withdrawals and even 90% in some countries such as India, Pakistan and Mexico (Fischer et al., 2007; Döll, 2009), has enabled farmers to improve crop output by approximately 40% (Leng and Tang, 2014). To feed a growing global population under a changing climate, irrigation water requirements (*WIRR*) will continue to increase in the next several decades to meet the rising food demand (Belder et al., 2004; Fischer et al., 2007). Hence, the water scarcity situation is likely to be exacerbated continuously, indicating that agricultural production and food security will face serious challenges (Tao et al., 2008). This situation makes it crucial to simulate the historical response of *WIRR* to climate change and project future *WIRR*, and further provide water resource management schemes. Therefore, the evaluation of potential consequences of climate change on *WIRR* has received considerable attention over the past decades (e.g., Yano et al., 2007; Fischer et al., 2007; Fleischer et al., 2008; Thomas, 2008; Tanasijevic et al., 2014; Ouda et al., 2015; Luo et al., 2015; Ye et al., 2015).

As a key element of soil water balance, crop evapotranspiration (ET_c) plays an important role in estimation and projection of *WIRR*. Therefore, the response of ET_c to climate change has also received a great deal of attention. For example, Cong et al. (2011) reported that ET_c will increase separately by 3.21% and 2.89% in east and central south China during 2046–2065 compared with that during baseline period (1961–1990). A study carried out by Tanasijevic et al. (2014) showed that in the Mediterranean countries, ET_c of olive was expected to increase by up to 8% in the middle of this century. Generally, although the specific change magnitude of ET_c in previous studies is highly dependent on local climate conditions, researchers had confirmed the significant increase of ET_c in the next several decades due to global warming. Along with the enhanced ET_c and the highly varied precipitation pattern under future climate change scenarios, remarkable increase of *WIRR* was found in a number of studies at the global sacle (Döll, 2002; Fischer et al., 2007) and the regional scale such as Bangladesh (Shahid, 2011; Mainuddin et al., 2015), Sri Lanka (De Silva et al., 2007), America (Elgaali et al., 2007) and China (Thomas, 2008; Zhu et al., 2015; Leng and Tang, 2014). For instance, Fischer et al. (2007) showed that *WIRR* would increase by about 50% and 16% in developing and developed countries, respectively. With the help of A1B emission scenario and daily soil water balance model, Mainuddin et al. (2015) found that *WIRR* of Boro rice would increase by up to 3% in the middle of this century.

China, the largest rice producer around the world, accounts for 18.5% of the world's rice-harvested area and contributes nearly 29.1% of rice production in the world (Faostat, 2011; Yu et al., 2012). As the most important rice planting zone in China, the middle and lower reaches of the Yangtze River (MLRYR) accounts for 49% of rice cropping area of this country (National Bureau of Statistics of China, 2015). In the MLRYR, there are three types of rice (early, late and single cropping rice) planting under two different rice-cropping systems (double cropping system and single cropping system). Traditionally, apart from the northern part of Jiangsu and Anhui province, most part of the study region belongs to double cropping system (Shen et al., 2011). Recently, given the inevitable influence of climate change on rice production, previous studies such as Shen et al. (2011) and Yang et al. (2015) have already explored the effects of climate change on rice yield in the MLRYR. However, the study on assessment the influence of climate change on rice *WIRR* is scarce in spite of the great significance of *WIRR* to the sustainable utilization of water resources and rice production security. Thus, it is urgent to quantify how climate change will affect the *WIRR* in the MLRYR, especially the investigation of the spatial distribution pattern of *WIRR* due to the complex spatial heterogeneity in climate conditions and rice varieties. Moreover, because of some social and economic reasons, such as shortage of workforce, the double cropping rice in the MLRYR has significantly decreased in the past decades, while the planting of single cropping rice increased obviously (Shen et al., 2011). Besides, along with the warming environment, the suitable double cropping region has expanded to northern part of the MLRYR (Ye et al., 2015). Therefore, it is necessary to investigate the influence of climate change on the *WIRR* for each type of rice planting in the whole region separately to provide deep insights into the sustainable utilization of water resources and food security.

Overall, the approaches used in previous studies to assess the impacts of climate change on *WIRR* can generally be grouped into two categories. The first one is driving crop models with GCMs data to simulate the responses of *WIRR* to climate change (e.g., Yano et al., 2007; De Silva et al., 2007; Wang et al., 2014). Crop models can characterize the dynamics of plant development process. However, crop models are always limited by the complexity in model structure and parameter estimation (Boote et al., 1996). Particularly, due to the spatial complexity of rice varieties in large study region, it is difficult to evaluate the spatial distribution of *WIRR* by crop model with limited field experimental data. The second one is driving the soil water balance model with future climatic input, which has been widely used in the evaluation of *WIRR* at large scale (e.g., Rodríguez Díaz et al., 2007; Zhu et al., 2015; Shahid, 2011). In this approach, effective precipitation is usually used to indicate the part of rainfall that can be used to meet the evapotranspiration of upland crops, such as wheat and maize. However, rice in the MLRYR is planted in submerged paddy field, in which a certain depth of water should always be maintained. Thus, the effective precipitation could not effectively reflect the utilization of precipitation in paddy field. Besides, the variability of crop phenology due to rising temperature has always not been taken into account in previous studies.

Therefore, in this study, considering the influence of climate warming on rice growing cycle, a specially developed rice growing length calculation method was used to simulate the days of growing period (*DGP*) of rice. Subsequently, daily water balance model and rice irrigation scheduling were jointly employed to detect the spatial patterns of the long-term trends of ET_c and *WIRR* for early rice, late rice and single cropping rice in the MLRYR under the happened climate change. Besides, the future change patterns of *DGP*, ET_c and *WIRR* were projected based on an ensemble of four GCMs under three representative concentration pathways (RCP) from the 5th Coupled Model Intercomparison Project (CMIP5). The results are expected to contribute to an in-depth understanding of how the irrigation water requirements response to climate change, especially in regional scales, which will serve as a reference for policymakers and stakeholders to put forward regional strategies on local water resource against the potential menaces of global change.

2. Materials and methods

2.1. Study area, soil, phenology and climate data

The middle and lower Reaches of the Yangtze River (MLRYR) is located between 24 and 35° N and 109–122° E, including six provinces (Jiangsu, Zhejiang, Anhui, Hubei, Hunan and Jiangxi) and Shanghai municipality (Fig. 1). Under the control of subtropical