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Responses of rice yield, irrigation water requirement and water use efficiency to climate change in China: Historical simulation and future projections

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ABSTRACT

Rice is one of most important crops in China, accounting for approximately 18% of total cultivated area. Rice productivity is significantly affected by undergoing climate change and vulnerable with water stress. Therefore, investigating the responses of rice growth and water resources utilization to more pronounced climate change is of great importance for water resources planning and management in terms of maintaining the ecosystem integrity and ensuring the food security. In this study, the changes of rice yield, water consumption (ET), irrigation water requirement (IWR), water use efficiency (WUE) and irrigation water use efficiency (IWUE) from 1961 to 2010 in three typical sites (Kunshan and Nanjing in the Yangtze River Basin, and Kaifeng in the Yellow River Basin) in rice plantation region of China were evaluated by means of validated rice crop model ORYZA2000. Their responses to future climate scenarios of 21 century were investigated by driving ORYZA2000 with downscaling climatic data from HadCM3 (Hadley Centre Coupled Model version 3) under A2 and B2 emission scenarios with the help of a statistical downscaling method (SDSM). The results exhibit a significant decline in rice yield was identified by 49.3 kg ha^{-1}, 32.0 kg ha^{-1} and 45.8 kg ha^{-1} for Kunshan station, Nanjing station and Kaifeng station, respectively, in the past 50 years due to obviously shortened rice growth duration (0.20 day a^{-1}, 0.15 day a^{-1} and 0.27 day a^{-1}, respectively). While changes of ET and IWE were different for three stations representing by significant increase of ET and IWE in Kunshan, non-significant increase in Nanjing and significant decrease in Kaifeng. Whereas accompanying production reduction, simulated WUE and IWUE for three stations all presented significant deceasing trends ranging from 0.06 kg ha^{-1} mm^{-1} to 0.16 kg ha^{-1} mm^{-1}. The future projection results under IPCC SRES A2 and B2 emission scenarios indicated the generally negative effect of climate warming to rice yield (maximum by −18.9% decline in 2090s in Kunshan) during the 21 century due to remarkable shortened growth period, resulting in generally depressed WUE and IWUE, although there would be the distinct response of the ET and IWR to future climate change for the three stations. Meanwhile, the increase of CO_2 concentration under future climate is beneficial to raise the rice yield, alleviate crop water consumption and irrigation water requirements and improve the water use efficiencies of rice in a certain degree. Further works should be carried out to capture simulation uncertainties in climate change impact assessment with consideration of interactions among anthropogenic activities, environmental and biological factors.

1. Introduction

Global atmospheric concentrations of greenhouse gases (GHG) have increased remarkably since 1750 and will continue to rise during the present century as a result of widespread human activities such as burning of fossil fuels, cement production, and land use change, which are stated by the most recent Intergovernmental

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Panel on Climate Change (IPCC) report (IPCC, 2007). Global mean temperatures have thus raised approximately 0.74 °C in the last 100 years and are expected to continually increase of 1.1–6.4 °C in this century (IPCC, 2007). This climate change mainly characterized by global warming has led to dramatic influences on both social and natural systems, causing overwhelming public concerns (Huntington, 2006; Papaioannou et al., 2011; Wang et al., 2012a,b). Among the suffering, water and agriculture sectors are likely to be the most sensitive ones to climate change-induced impacts, especially in China (IPCC, 2001; Tao et al., 2003; Piao et al., 2010). Under the background with CO_2 concentration increase and climate warming, the agriculture and crop production may be affected through the changes of physiological processes including photosynthesis, respiration and partitioning of photosynthesis production due to the soil and air conditions alteration (Chartzoulakis and Psarras, 2005; Yang and Zhang, 2006; Guo et al., 2010). Meanwhile, the patterns of the irrigation water requirements (IWR) and water use efficiency (WUE) should be changed since the balance between precipitation, evapotranspiration and the resultant fluctuations have been broken due to the alteration of rainfall patterns, soil moisture and other relevant climate variables such as humidity, windiness and cloudiness under global warming (Komuscu et al., 1998; Silva et al., 2007). In fact, from a water resources perspective, the alterations of precipitation, runoff, infiltration, groundwater flow, evapotranspiration, and soil moisture in many parts of the world during the past century suggest climate change is leading to an intensification of regional hydrological cycles and could have major impacts on water resources, affecting both ground and surface water supply irrigation and agricultural system (Alan et al., 2003; Huntington, 2006).

With rising concerns over food security, exploring the effects of climate change on agriculture has been widely attempted and the relative efforts mainly focused on estimating changes in crop productivity (e.g., Brumbelow and Georgakakos, 2001; Tao et al., 2006; Hussain and Mudasser, 2007; Challinor and Wheeler, 2008; Mo et al., 2009; Liu et al., 2010). Three different ways are usually used to investigate the response of crop yield to climate change, which are summarized though reviewing the related studies widespread in the world. First, exploring the evidences of crop response to climate change by correlative analyzing observation between crop yield and climate change directly (e.g., Peng et al., 2004; Tao et al., 2006; Egli, 2008; Malone et al., 2009). Second, examining crop yield change under different climate inputs with using weather generator to drive a crop model (e.g., Stockle et al., 1997; Zhang and Liu, 2005; Kou et al., 2007; Tao et al., 2008). The third and also the most prevalent method is to drive crop model with the future climate information from GCMs to simulate the response of crop yield in the future (e.g., Trnka et al., 2004; Xiong et al., 2007, 2008; Silva et al., 2007; Chavas et al., 2009; Mo et al., 2009; Shen et al., 2011). Climate change is found to have significant impacts on environments and conditions affecting crop productivity in China. Although some aspects of climate change such as longer growing seasons (Xiong et al., 2007), increasing atmospheric CO_2 (Liu et al., 2010), warmer nighttime temperatures and higher precipitation (Thomson et al., 2006) may bring benefits in some regions, there will also be a range of adverse impacts, including reduced water availability (Bouman et al., 2007), greater water need (Piao et al., 2010), and more frequent extreme high temperature (Shen et al., 2011). These impacts may put agricultural activities at significant risk (Eitzinger and Kubu, 2009; Mimi and Jamous, 2010).

Compared with the studies on the response of crop yield to climate change, the assessment on changing water resources use, irrigation water demands and requirements in agriculture field started later, and have been fewer in number (Wang et al., 2012a). Brumbelow and Georgakakos (2001) assessed changes in irrigation requirements and crop yields for five traditional crops of the United States by combining the crop model and different climate modeling and indicated variability in both irrigation demands and crop yields increases. Tao et al. (2003) explored the changing trends in agricultural water demands, the changing trends and variability in soil moisture associated with both drought and increased surface runoff in China croplands during the second half 20th century. Döll (2002) presented the first global analysis of impact of climate change on irrigation water requirement using a developed global irrigation model. As a function of both projected irrigated land and climate change, Fischer et al. (2007) computed the future regional and global irrigation water requirements from 1990 to 2080. More recently, Thomas (2008) modeled the effects of climate change on irrigation requirements with high-resolution girded climate data sets.

Rice is the main food staple in Asia where more than half of the world's population resides (Bachelet et al., 1992), particularly in China, where rice is the staple food for more than 65% of Chinese population (State Environmental Protection Administration, 2003). Although the rice cropping area represents only 29.1% of the total national crop growing area, rice production contributes 43.7% of total national grain production, representing 22.8% and 36.9% of the total world cropping area and production respectively (Xiong et al., 1992; Yao et al., 2007). Unfortunately, climate change and its impact on rice production, limiting the capacity of farmers to grow this crop, is a big challenges China and the rest of the world will have to face (Peng et al., 2004; Tao et al., 2008; Piao et al., 2010). Therefore, the vulnerability of rice production to global change has become of key concern with extensive studies being conducted in simulating the impact of climate change on rice production in Asia, especially in China (e.g., Lin et al., 2005; Yao et al., 2007; Tao et al., 2008; Xiong et al., 2009; Shen et al., 2011). However, past assessments have mostly focused on change in crop yield, and few studies have assessed changing irrigation requirements and water use efficiency. Moreover, most assessment has employed climate scenarios from GCM with a coarse resolution to point-based crop model, suggesting it is necessary to add fine-scale local climate information to the coarse-scale one to derive the crop model (WMO, 2002; Yao et al., 2007).

Therefore, the objectives of this paper are to: (1) explore how the past climate change has impacted the rice growth processes, irrigation water requirements, and water use efficiencies with a modeling approach that enables the assessment of climate change impact with fixing rice varieties and management practices at three typical sites of the rice plantation areas in China, (2) conduct a comprehensive analysis on how the rice yield, irrigation water requirements and water use efficiency response to climate change under future climate scenarios accompanying CO_2 concentration enrichment. For this, a widely use rice crop model, ORYZA2000, was calibrated with experiments data. Meanwhile, the statistical downscaling method (SDSM) are used to create daily weather series from the HadCM3 (Hadley Centre Coupled Model version 3) model under A2 and B2 emissions.

2. Materials and methods

2.1. Study area

In this study, three typical rice ecological stations with geographical and climatological differences, i.e., Kaifeng, Nanjing and Kunshan, were selected to simulate the effects of climate change on rice growth and water utilization (Fig. 1). Kaifeng (34°82′N, 114°51′E; 69.0 m a.s.l.) is located in the southern bank of the Yellow River, while Nanjing (32°00′N, 118°28′E; 7.1 m a.s.l.) and Kunshan (31°23′N, 120°58′E; 17.5 m a.s.l.) belong to the middle and lower reaches of the Yangtze River Basin. All the three stations distribute