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APCC RESEARCH REPORT 2013-07

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PREFACE

It is our pleasure to present this report on the APEC Climate Center (APCC)'s research activities in 2013, which has been a very productive year for our Center.

APCC has expanded its research scope, in response to regional societal and scientific needs. While building expertise in climate prediction remains a priority, we are extending our reach to include policy-relevant climate applications and value-added climate information products.

APCC has accelerated efforts to better our service to the region. As one of the main services provided by APCC, the MME 3-month prediction information has been productively applied by scientists in developing countries that are unable to produce their own prediction information. Furthermore, in order to better prepare for climate-related hazards in a timely manner, APCC launched its 6-month MME prediction service in September 2013. We also began to release forecasts of the Boreal Summer Intraseasonal Oscillation (BSISO), starting from July 2013, as the world's first operational BSISO forecast service. Our researchers also achieved great success in publishing their papers in noted academic journals. Dr. Ok-Yeon Kim, for example, published a paper in *Climate Dynamics* and her research was later selected as one of the Research Highlights by another distinguished journal, *Nature Climate Change*. The following research report provides more information about our research outcomes from 2013.

We will continue to promote the best use of our research outcomes in various scientific and application areas. Our successes and achievements would not have been possible without the support of our valued partners. In this regard, I extend my thanks to you and I hope you enjoy this 2013 Research Report.

Chin-Seung Chung
Director, APEC Climate Center

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Development of a Regional Rice Model for Assessing the Impact of Climate Change on Rice in South Korea

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RESEARCH REPORT 2013-07

Development of a Regional Rice Model for Assessing the Impact of Climate Change on Rice in South Korea

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ABSTRACT

A large area rice model was developed based on the existing GLAM-wheat framework to assess the impact of climate change on rice in South Korea. The newly developed GLAM-rice model can capture much of the variability of observed rice yield at the provincial level. Climate variables from the regional climate model YSU-RSM performed well in our climate impact study for South Korea, and these variables were used in the GLAM-rice model to assess the impact of climate change on rice in South Korea. Climate change could result in a 5.9 to 7.7% reduction of rice yield in South Korea by 2050. The negative impact of climate change on rice can be offset by the CO_2 fertilization effect. To improve rice yield, adaptation strategies, including changes in planting dates and use of earlier and later maturing rice varieties, were implemented. Adjusting the planting dates to 20 days earlier results in only a small increase in rice yield. Use of later maturing rice can lead to 14.9 and 14.2% increases in rice yield for the rcp4.5 and rcp8.5 climate scenarios, respectively. To improve rice yield and meet future food demands, alternative options for rice crop adaptation and the support of government policies, remain necessary for South Korea. Even if total rice production increases with adaption, it may still be insufficient to meet the requirement of an increasing population. The goal of the South Korean government is to achieve food sovereignty thus increasing total grain production and maintaining food security is a critical issue.

1. INTRODUCTION

Climate and weather are important factors affecting agricultural productivity. Crop growth, development, and yield will be affected by climate and weather conditions once a certain threshold (e.g., temperature, water stress) is exceeded (Porter and Semenov 2005). Global mean crop yield is already being affected by climate change (Lobell and Field 2007). Future climate change and variability will exert significant impact on agricultural production, and consequently influence crop yield, food supply, and response strategies at global and regional levels (Pimentel 1993). Seasonal forecasting of crop yield and assessment of climate impact on crop production are the important processes in food risks assessment and optimization of management using climate predictions. Substantial studies have investigated the potential impact of climate change on agriculture, at global (Rosenzweig and Parry 1994; Parry et al. 1999) and national or regional scales (Adams et al. 1990; Alexandrov and Hoogenboom

2000; Reilly et al. 2003). However, most of these global and regional impact studies were based on site-specific estimates of yield; regional/national level yields were obtained simply by up scaling results from site-specific simulations. Thus, the detailed spatial changes in yield variability may not be captured at the regional level when, for example, complex topography and large spatial variations in weather and climate are present. Regional or global impact studies at fine resolutions are still essential. Crop models have been widely used to assess the possible impact of climate change and variability on crop production (Lin et al. 1997; Hulme et al. 1999; Xiong et al. 2001). The traditional crop model is designed to simulate crop yield at the specific-site level. There is a growing need for regional or large-scale impact studies for assessing adaptive capacity (Kates and Wilbanks 2003) and for use in decision making (Easterling and Polsky 2004). Scaling up crop model simulations (Hansen and Jones 2000) or model inputs (Jagtap and Jones 2002) from site level to regional scales is required for regional impact studies. However, most of the dynamic crop models have high data input requirements and aggregating the spatial variability of input variables from the field scale to the regional scale is complex. Although numerous studies on the impact of climate change on agricultural productivity have been conducted, assessments of the future climate impact are still limited by the ability of the crop models, accuracy of the input data, and uncertainties in the climate change scenarios. With the improvement of GCM (Global Climate Model) crop models and quality of historical weather data, prediction of crop yield will become more reliable.

The general large-area model for annual crops (GLAM) has been developed for directly simulating groundnut and wheat yield at the regional level (Challinor et al. 2004; Li et al. 2010), providing a framework for developing - a rice crop model at the regional level. Thus, the regional rice model GLAM-rice will be developed to assess the impact of climate change on rice at larger spatial scales.

Rice is one of the most important and most widely grown crops in Korea. Rice production accounts for about 90% of total grain production and 40% of farm income. To understand how climate variables affect rice yield, it is important to analyze the relationship between climate and rice in the current climate. The purpose of this study is 1) to analyze the relationship between climate and rice in current climate conditions in South Korea, 2) to develop the regional rice model, and 3) to evaluate the overall impact of climate change on rice yield at the national level for Korea in order to provide more effective adaptation strategies.

2. DATA AND METHODOLOGY

2.1 An overview of GLAM

GLAM is a process-based regional crop model with a daily time-step simulation. The model simulates the soil water balance, leaf canopy and root growth, biomass and yield production, which are limited yield gap parameters, inadequate soil water, and extremes in temperature. Figure 1 shows a flowchart of the GLAM model structure and the processes of yield and biomass formation. In GLAM, crop yield is simulated daily as the product of accumulated biomass and the harvest index (the ratio of grain yield to biomass). After grain-filling, the harvest index is assumed to increase linearly with time, and is limited by high temperature stress. Biomass is accumulated through transpiration and transpiration efficiency. Transpiration is affected by temperature, total solar radiation, available soil water, leaf area index (LAI), and root growth. The LAI is reduced by soil water stress and by the yield gap parameter from the physiological maximum value to an effective value.

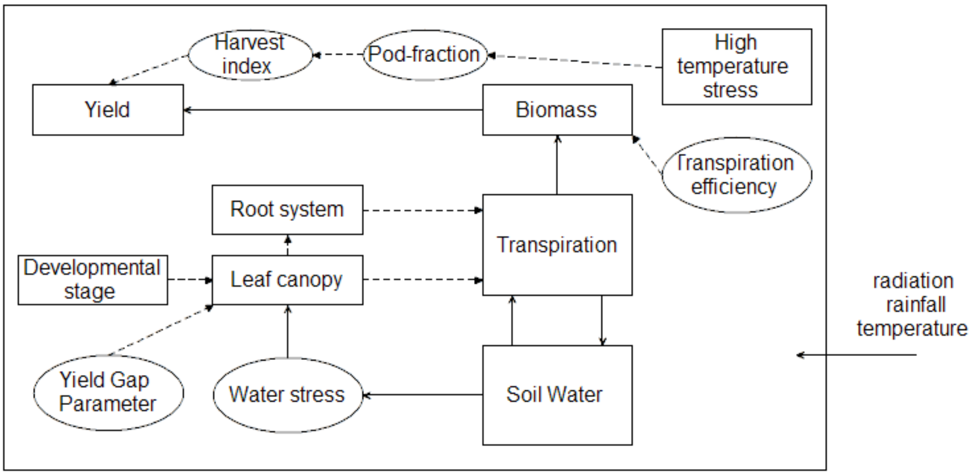

Figure 1 Schematic diagram of the relationships among the variables influencing growth and yield in GLAM. Rectangles represent state variables; ovals represent auxiliary variables. Solid lines represent flow of material; dashed lines represent flow of information.

The sowing date and yield gap parameter are two important model parameters of the GLAM model. Sowing dates are determined by the local calendar and soil moisture. The yield gap parameter, C_{YG}, varies within a range of 0.05-1. The optimal value in each grid cell is chosen by minimizing the Root Mean Square Error (RMSE) between observed yields and simulated yields. The main daily model outputs are leaf area index (LAI), root depth, potential and actual evapotranspiration, soil water balance, yield, and biomass. The descriptions of crop development, crop growth, evapotranspiration, and a detailed description of model formation can be found in Challinor et al. (2004).

In GLAM, the above-ground biomass (W) is accumulated through actual transpiration (T_T), the least favorable transpiration efficiency ($\frac{E_T}{V}$), and the maximum transpiration efficiency ($E_{TN,max}$), as shown by Eq. 2.1.

$$\frac{\partial W}{\partial t} = T_T \min\left(\frac{E_T}{V}, E_{TN,\max}\right) \tag{2.1}$$

where W (kg ha^{-1} day^{-1}) is the daily crop above-ground biomass production, E_T (Pa) is the normalized transpiration efficiency (i.e., V × transpiration efficiency in g kg^{-1}), V (kPa) is the daily mean vapor pressure deficit (VPD = $e_{\mathrm{sat}}(\overline{T}) - e$, where e is the vapor pressure), and $E_{TN,max}$ (g kg^{-1}) is the maximum transpiration efficiency. T_T (cm day^{-1}) is the daily actual transpiration, which is affected by the temperature, LAI, root growth, and available soil water.

$$Y = HIW \tag{2.2}$$

where Y is yield (kg ha^{-1}), which is produced by the harvest index (HI) and above-ground biomass (W).

2.2 Development of GLAM-rice

2.2.1 Model development processes

Based on the framework of GLAM-wheat, a large area rice model was developed by modifying some model parameters and defining rice development and growth processes (Figure 2). GLAM-rice was developed in three stages. The first stage was collecting the rice growth and development parameter sets from the literature and experimental data (Table 1). Parameter values that were not available in the literature were determined by calibrating parameters against the experimental datasets. The second stage was incorporating the soil water balance in paddy rice fields from ORYZA2000 into GLAM to simulate water balance of the lowland paddy rice. The third stage was parameterizing the rice growth and developmental processes, such as defining the leaf area growth of rice, incorporating the effect of temperature on rice leaf growth, considering the effect of photoperiods and their interaction with temperature on the development of rice, and parameterizing the CO_2 fertilization effect on rice growth. Finally, the performance of the new GLAM-rice model is examined by comparing the simulation with observations.

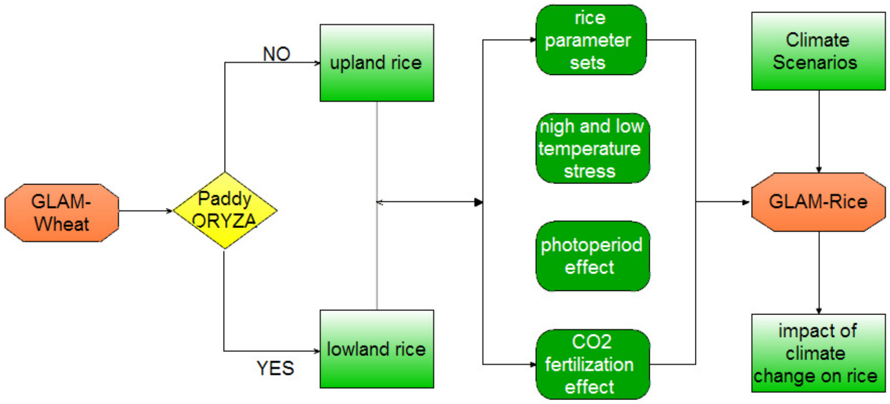

Figure 2 Development of GLAM-rice based on the existing GLAM-wheat framework.

Table 1 New values for the parameters used in GLAM-rice, and source of information.

Parameters	Description	Value	Source
DLDTMX	Maximum LAI expansion rate	0.08-0.18	calibration
TE	Transpiration efficiency (kPa kg m^{-3})	6	Sinclair, 1998
P_TRANS_MAX	Max value of pot. Trans (cm)	0.6	Wang et al. 2004
TEN -MAX	Maximum Transpiration efficiency (g kg^{-1})	5.9	Yoshida 1975
DHDT	Rate of change in harvest index	0.01	calibration
C_{ph}	Critical photoperiod (hours)	11.5	Bouman et al. 2001
TB	Base temperature(°C)	8	Gao et al. 1992
TO	Optimum temperature (°C)	30	Gao et al. 1992
TM	Maximum temperature (°C)	42	Gao et al. 1992
T_{max}	Maximum temperature for flowing (°C)	35	Matsui and Horie 1992
ZRTTR	root depth at transplanting (m)	0.05	Boling et al. 2000
ZSMAX	Maximum root length (cm)	57	Chaitra et al. 2006

2.2.2 Development of leaf area index (LAI)

In GLAM, LAI is simulated through an LAI expansion rate, which is assumed to be constant under optimal conditions, and reduced by sub-optimal temperature, water stress, and the yield gap parameter. The leaf area in rice reaches a maximum size near flowering, and then senescence begins. The leaf area development process in GLAM-rice was modified from that of wheat. In spring wheat, leaf area growth is limited only by water availability and the yield gap parameter. However, leaf area expansion in rice is also controlled by temperature, particularly early in the season. Hence, the equation for LAI accumulation of rice included a temperature effect. Generally, water stress can accelerate senescence of leaf area. Therefore, the growth of the rice leaf area was determined as follows:

$$\frac{\partial L}{\partial t} = \begin{cases} RLAIFLT \times (Tm - Tb) \times C_{YG} \times LESTRS & \text{LAI} < 1 \quad i = 0,1 \\ \left(\frac{\partial L}{\partial t}\right)_{\text{Emax}} \times C_{YG} \times LESTRS & \text{LAI} \geq 1 \quad i = 0,1 \\ -\left(\frac{\partial L}{\partial t}\right)_{\text{Smax}} \times C_{YG} \times (2 - LESTRS) & i = 2,3,4 \end{cases} \tag{2.3}$$

Where *RLAIFLT* is leaf growth rate per degree temperature, L is the effective LAI (m^2 m^{-2}), $(\partial L/\partial t)_{E\max}$ is the maximum leaf expansion rate ($m^2 m^{-2} day^{-1}$), which is a prescribed constant, $(\partial L/\partial t)_{S\max}$is the maximum leaf senescence rate (m^2 m^{-2} day^{-1}), and C_{YG} is the yield gap parameter (YGP), *LESTRS* is the water stress factor on leaf area growth, from the water balance model of paddy ORYZA2000, T_m(°C) is the daily mean temperature, and T_b (°C) is the base temperature. The growing period of rice was divided into five general growth stages: sowing to panicle initiation (i=0), panicle initiation to flowering (i=1), flowering to grain-filling(i=2), grain-filling to the end of grain-filling(i=3) (physiological maturity), and the end of grain-filling to harvest maturity (i=4).

2.2.3 Incorporating water balance of paddy into GLAM

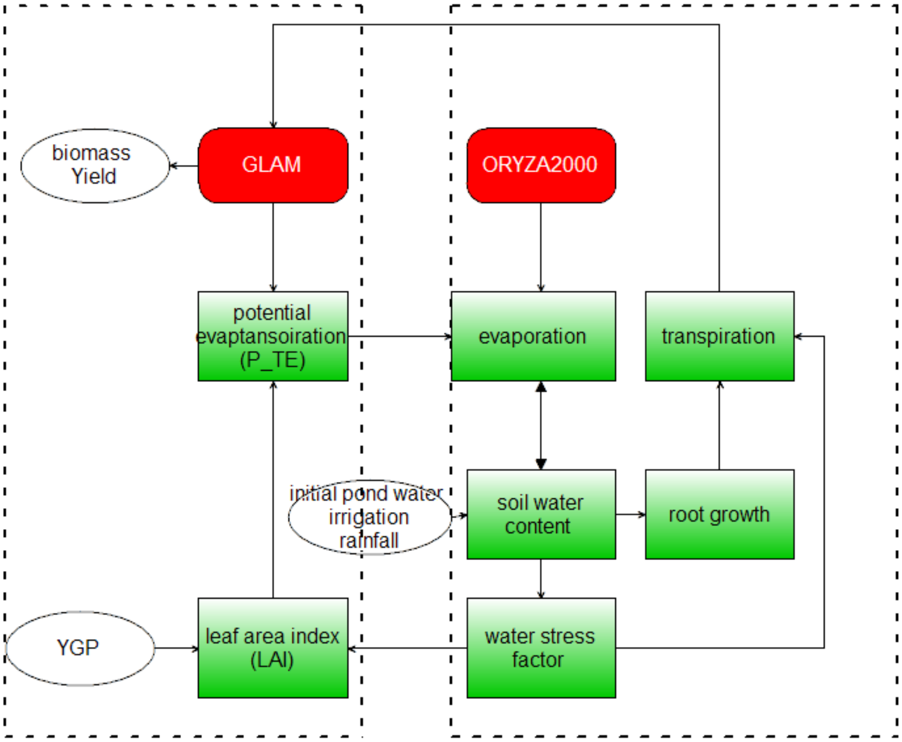

Figure 3 Interface linking GLAM-rice to the water balance model of paddy from ORYZA2000.

The water balance of paddy is different from the water balance of field crops because paddy requires standing water in the field during the rice growth period. The crop model ORYZA2000 is a widely used crop simulation model that simulates the growth, development, and water balance of lowland rice. It simulates various water balance components such as the depth of ponded water, evapotranspiration, deep percolation, capillary rise, surface runoff, and depth of irrigation water and groundwater at daily increments (Bouman et al. 2001). A detailed of description of the model formation can be found in Bouman et al. (2001). The water balance model of paddy from ORYZA2000 rice model was incorporated into GLAM to simulate the soil water balance of lowland rice. Figure 3 shows the connection between

GLAM-rice and the water balance model of paddy from ORYZA2000. First, GLAM simulates potential evapotranspiration using the simpler Priestley-Taylor equation (Priestly and Taylor 1972), and the potential evapotranspiration is partitioned into potential transpiration and potential evaporation according to LAI and available soil water. Then, the potential transpiration and potential evaporation from GLAM are used as inputs for the water balance ORYZA2000 model of paddy to simulate soil water content, water stress factor, transpiration, and evaporation. In turn, the water stress factor and transpiration from the water balance of paddy is used in GLAM to reduce the leaf area index and produce biomass. The water balance of paddy from ORYZA2000 is determined as follows:

$$inflow = irrigation + rainfall + capillary\ rise + ponded\ water \quad (2.4)$$

$$outflow = evaporation + transpiration + seepage + percolation + surface\ drainage + runoff \quad (2.5)$$

$$dW = inflow - outflow \quad (2.6)$$

$$WCL(I) = WCL(I) + dW(I)/TKL(I) \quad (2.7)$$

Where (all units in mm day^{-1}) *WCL(I)* is the soil water content of each soil layer, *dW(I)* is the change in stored water, *TKL(I)* is thickness of each soil layer, and *I* is the soil layer.

2.2.4 Effect of photoperiod on rice development

Research has shown that photoperiod and temperature can affect plant development (Yan and Wallace 1995). Rice is a short day plant. The development rate of photoperiod-sensitive species will be reduced when the day length is longer than a critical value. The daily relative photoperiod effectiveness (R_{pe}) is affected by the photoperiod sensitivity of the plant variety, effective photoperiod hours, and critical photoperiod hours. The development rate of rice is delayed when the day length is longer than 11.5 hours, which is the critical photoperiod of rice (Bouman et al. 2001). The daily relative photoperiod effectiveness (R_{pe}) is estimated according to the following equations:

$$D_{ec}=0.4093\times SIN\ (0.0172\times\ (D_{OY}-82.2)) \tag{2.8}$$

$$D_L=\ (-SIN\ (0.01745\times Lat)\ \times\ SIN\ (D_{ec})-0.1047)\ /\ (COS\ (0.01745\times Lat)\ \times\ COS\ (D_{ec})) \tag{2.9}$$

$$P_h\ =7.639\times ACOS\ (D_l) \tag{2.10}$$

$$R_{pe}=1-P_s\times\ (P_h-C_{ph}) \tag{2.11}$$

$$TTA = \sum DTT \times R_{pe} \tag{2.12}$$

Where D_{ec} (radians) is the sun declination, D_{OY} is the day of year, D_L (hours) is the day length variable, Lat is the latitude, P_s is the photoperiod sensitivity and P_h (hours) is the effective photoperiod hours, expressed using the function from Ritchie (1991), R_{pe} is the daily relative photoperiod effectiveness, C_{ph} (hours) is critical photoperiod hours, TTA (°Cd) is the thermal time accumulation, and DTT (°Cd) is the daily thermal time.

2.2.5 Temperature stress on rice

Low and high temperature stress can affect the spikelet formation and finial gain yield of rice. Between the booting and flowering stages, rice is quite sensitive to low temperature stress. According to study of Horie et al (1992), spikelet sterility of rice increases with accumulation of cooling degree-days, when the daily average temperature is below a critical value (Uchijima 1976). The cooling degree-days (COLDTT; °Cd) and the percentage sterility caused by cold (S_c) are calculated as follows:

$$COLDTT=\ \sum_{p}^{f}(22-\mathrm{Td}) \tag{2.13}$$

$$S_c=1-(4.6+0.054\times COLDTT^{1.56})/100 \tag{2.14}$$

Where $COLDTT$ is the cooling degree-days, Td is the average temperature, P and F are the dates of panicle initiation and flowering, and S_c is the percentage sterility caused by cold.

Even short episodes of high temperature can have a dramatic impact on crop yield, especially at anthesis, when plants are vulnerable to high temperature stress (Ferris et al. 1998). In rice, exposure to high maximum temperature (>35 °C) episodes near flowering can result in a reduction in pollination (Satake and Yoshida 1978; Matsui and Horie 1992). Since rice yield is vulnerable to extreme high temperatures during flowering, it is necessary to parameterize the high temperature stress on rice growth to assess the future climate impact on crop productivity, especially for tropical regions.

In GLAM, the impact of high temperature on wheat flowers has been parameterized and assessed by Li et al. (2010). This subroutine was modified to simulate the effect of low and high temperate stresses on rice based on previous experiments and ORYZA2000. Equations 2.13-2.15 are the same as ORYZA2000. During flowering, the grain-set fraction of rice will decrease when the daily maximum temperature (T_{max}) is above a critical value. Consequently, the rate of change of the harvest index will be reduced when grain-set fraction is below a critical value, resulting in a reduction in the harvest index potential grain yield. The effect of high temperatures stress on the fraction of rice fertile spikelets (S_h) is estimated by the follow equation:

$$S_h=1/\ (1+\exp\ (0.853(T_{max}-36.6) \qquad (2.15)$$

The rate of change of the harvest index is also reduced when the fraction of rice spikelet is lower than a critical value, leading to a reduction in harvest index and potential grain yield. The relationship between the harvest index and the fraction of rice spikelet is estimated by following equation:

$$\frac{\partial H_I}{\partial t}=\left(\frac{\partial H_I}{\partial t}\right)_0\left(\frac{1-P_{cr}-MIN(S_c,S_h)}{P_{cr}}\right) \text{ for MIN } (S_c,\ S_h)<P_{cr} \qquad (2.16)$$

Where $\frac{\partial H_I}{\partial t}$ is the rate of increase in harvest index. When the grain set fraction is below a critical fractional grain-set P_{cr}, the non-stressed value of rate of increase in the harvest index $\left(\frac{\partial H_I}{\partial t}\right)_0$ is reduced. The value of P_{cr} is in the range of 0.6-0.8.

2.2.6 Parameterization of the CO_2 effect

Plant growth is directly influenced by enhanced CO_2 concentrations through stimulation of photosynthesis and reduced transpiration, and is hence improved by water use efficiency (Rosenberg et al. 1990). In GLAM, photosynthesis is not modeled directly, but it is represented by the transpiration efficiency. The transpiration efficiency (*TE*) was increased to simulate the response of the crop to the elevated CO_2 (Challinor and Wheeler 2008). According to the results of the FACE (Free-Air Carbon dioxide Enrichment) experiment in China, rice biomass increased by 28.9%, and there was a 10% reduction in transpiration at 570 ppm CO_2 and high nitrogen levels (Pang et al. 2006), suggesting that there is a 43% increase in transpiration efficiency (*TE*) in rice at 570 ppm CO_2. When CO_2 is elevated, the change in the maximum transpiration efficiency depends on the increase in transpiration efficiency, as showed by Challinor and Wheeler (2008):

$$\begin{aligned} E_{TN,max} &= (1 - T_{fac})\, E^{c}_{TN,\max} + T_{\mathrm{fac}} E_T\, E^{c}_{TN,\max} \,/\, E^{c}_{T} \\ &= E^{c}_{TN,\max} + T_{\mathrm{fac}}\, E^{c}_{TN,\max}\, (E_T / E^{c}_{T} - 1) \end{aligned} \tag{2.17}$$

Where the superscript c indicates the calibrated values under the current climate, T_{fac} is defined as the $E_{TN,max}$ change fraction relative to an increase in transpiration efficiency, E_T, in elevated CO_2 conditions, with a value from 0 to 1. For $T_{fac}=0$, $E_{TN,max}$ is unchanged compared to its baseline value. For $T_{fac}=1$, $E_{TN,max}$ increases by the same fraction as E_T.

When CO_2 levels are doubled, a value of T_{fac} in the range of 0.3-0.5 was suggested by Chen et al. (1990) and Cox et al. (1999). Therefore, $T_{fac}=0.4$, and 43% increases in *TE* are the parameter changes used in GLAM to simulate the effect of CO_2 fertilization on rice yield for 570 ppm CO_2.

2.3 Data source and methods

An observed provincial-level rice yield database for South Korea is available for 1980 to 2011 from the Korean statistical database (http://kosis.kr). Station weather data is available from the Korean Meteorological Administration. In order to run GLAM-rice at the provincial level for South Korea, station weather data from 60 stations such as daily rainfall, maximum temperature, minimum temperature, and solar radiation in the main rice growing regions were aggregated to the provincial level. The simulated provincial level rice yield will then be compared to the observed yield to evaluate the performance of GLAM-rice. The optimal value of the YGP in each province was chosen by minimizing the RMSE between observed and simulated yields for the periods 1980-1995 and 1996-2011. Two-fold cross-validation was used to evaluate the performance of GLAMA-rice at the provincial level from 1980 to 2011.

The daily weather inputs used by GLAM are the maximum and minimum temperatures, precipitation, and solar radiation. The daily vapor pressure deficit (VPD) was calculated using the daily maximum and minimum temperatures. The grid climate data used in this study was from CORDEX-East Asia (Coordinated Regional climate Downscaling Experiment). CORDEX-East Asia is the East-Asian branch of CORDEX and has produced ensemble climate simulations based on multiple dynamical and statistical downscaling models forced by global climate models (http://cordex-ea.climate.go.kr/main/mainPage.do). In order to validate the performance of GLAM-rice, climate variables from CORDEX-East Asia were used in this study to force the crop model. The daily maximum and minimum temperatures, rainfall, and solar radiation from regional climate models YSU-RSM, RegCM4, SNU-MM5, and HadGEM3-RA at 0.44 × 0.44 degree scale (see Table 2 for details) were re-gridded to 0.25 × 0.25 degree scale, and were used to run GLAM-rice for South Korea for 1991-2000. Rice yield at the provincial level in all of South Korea from 1991 to 2000 was aggregated to a 0.25 × 0.25 grid yield using ArcGIS. First, GLAM-rice was calibrated by running the model with the climate variables from YSU-RSM, RegCM4, SNU-MM5, and HadGEM3-RA for 1991 -1995. The yield gap parameter in each grid cell is calibrated by minimizing the root mean square error between observed and simulated rice yield at 0.25 × 0.25 degree scale for 1991-1995. Then, GLAM-rice was validated for 1996-2000 using the calibrated yield gap parameters for 1991-1995 at 0.25 × 0.25 degree scale for South Korea.

Table 2 Description of climate simulations used in this study.

GCM	Downscaling models	Institute	Resolution	Periods
HadGEM2-AO	YSU-RSM	Yonsei University	0.44 degree	1991_2000 2041_2050
HadGEM2-AO	RegCM4	Kongju National University	0.44 degree	1991_2000
HadGEM2-AO	SNU-MM5	Seoul National University	0.44 degree	1991_2000
HadGEM2-AO	HadGEM3-RA	National Institute of Meteorological Research	0.44 degree	1991_2000

HadGEM2-AO	: the Atmosphere-Ocean coupled Hadley Center Global Environmental Model version 2 from the National Institute of Meteorological Research (NIMR)
RegCM4	: The Regional Climate Model version 4, developed by the International Centre for Theoretical Physics (ICTP)
YSU-RSM	: Yonsei University, NCEP Regional Spectral Model (RSM)
SNU-MM5	: Seoul National University, Meso-scale Model version 5
HadGEM3-RA	: the regional version of the new seasonal prediction and prototype global climate model HadGEM3

In order to assess the impact of climate change on rice in South Korea, GLAM-rice is applied for three completely different climate change scenarios: the baseline (1991-2000), and the 2040s (2041-2050) under two emission scenarios (typically, rcp4.5 and rcp8.5). In this study, the predictions of future climate change impact on rice yield are based on the assumptions that the optimal yield gap parameter (YGP), sowing dates, and area of rice in the future scenarios are the same as those for the baseline.

3. RESEARCH RESULTS

3.1 Rice production and the relationship between rice and climate

Agriculture accounted for about 5% of South Korea's GDP in 2000 (http://data.worldbank.org/). In South Korea, rice is the largest crop. Rice represented about 89% of crop production and 81% of crop growing area in 2000. From 1960 to 2000, the national rice yield in South Korea showed a rising trend, increasing at an average rate of 1518 kg ha^{-1} 10y^{-1} from 1960 to 1980. In 1980, there was a great reduction in rice yield due to low temperature damage, and the rate of increase for 1981-2009 was much lower than for 1960-1980 (Figure 4). This was because after 1980, South Korea began to focus more on rice quality rather than on quantity. After 1988, there was a decline in rice production, from about 8.2 million tons in 1988 to 5.4 million tons in 2012, mainly due to a reduction in harvest area (Figure 5). This resulted from the rising costs of rice production, e.g., rising costs of labor, services, farm implements, and fertilizer (Figure 6).

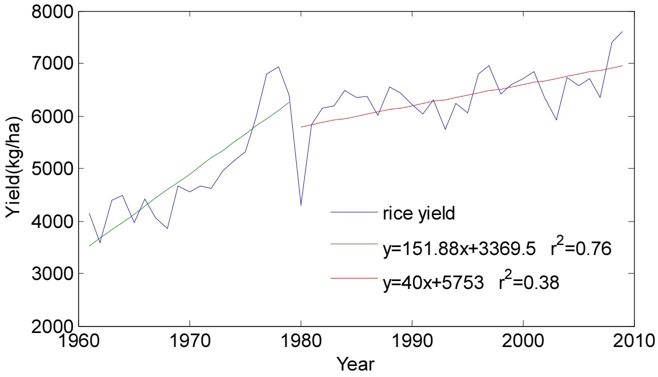

Figure 4 Time series of national rice yield in South Korea, with two linear functions fit to yield for 1960-1980 (green line) and for 1981-2009 (red line). Dataset is from the Korean statistical database (http://kosis.kr).

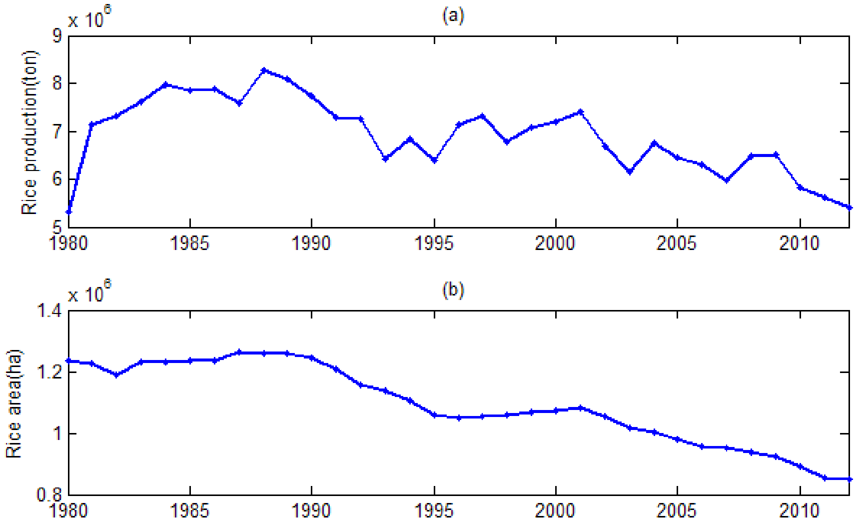

Figure 5 (a) Total rice production (ton) in South Korea from 1980 to 2012. (b) Total rice harvest area (ha) in South Korea from 1980 to 2012. Dataset is from the Korean statistical database (http://kosis.kr).

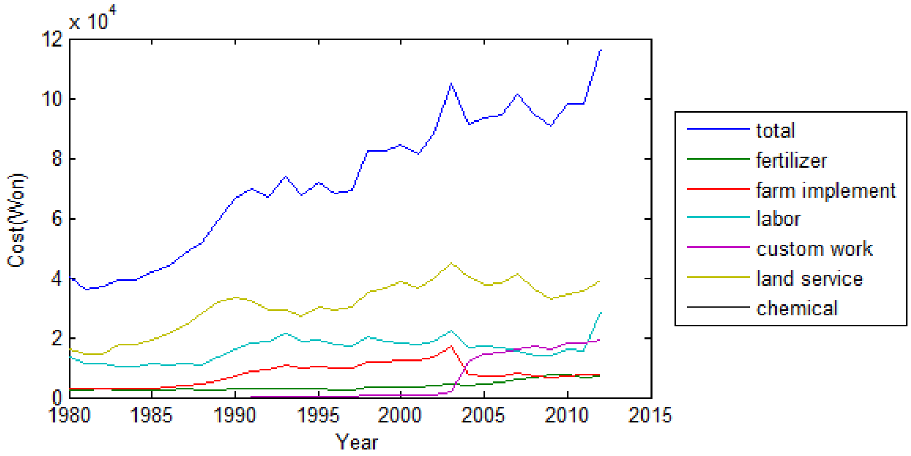

Figure 6 The cost of rice production from 1980 to 2012 in South Korea. Dataset is from the Korean statistical database (http://kosis.kr).

To assess the impact of temperature on rice yields in South Korea, the response of rice anomalies to temperature and rainfall anomalies from 1960 to 2009 were analyzed. Yield of rice anomalies (detrended yield) are obtained by removing the technology trend from the original yield. At the national level, there was a significant positive correlation ($r = 0.42$, $p < 0.05$) between rice yield and seasonal mean temperatures (Figure 7b). In South Korea, low temperature is one of the main limiting factors affecting rice production. An increase in temperature can stimulate growth of rice and consequently increase rice yield thus, the current warming trend has a positive impact on rice yield in cool regions such as South Korea. In contrast, the rice yield anomalies did not show significant correlation with seasonal total rainfall (Figure 7a) because rice is irrigated in most of South Korea. Therefore, rice yield variability in South Korea is mainly affected by variability in temperature, and yield fluctuations can be partly explained by temperature anomalies.

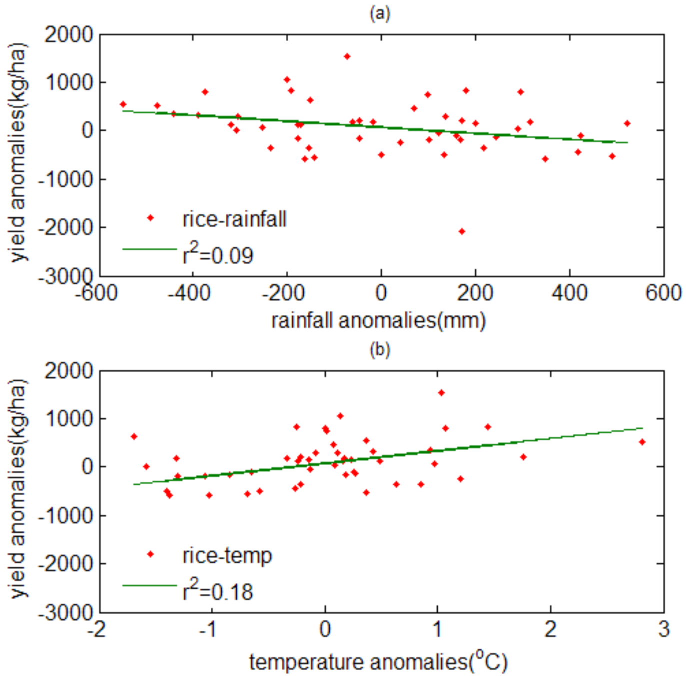

Figure 7 (a) Correlation between seasonal total rainfall anomalies and national rice yield anomalies for 1961-2009 in South Korea. (b) Correlation between seasonal mean temperature anomalies and rice yield anomalies for 1961-2009 in South Korea.

3.2 Validation of GLAM-rice

3.2.1 Calibration of GLAM-rice

In GLAM, LAI is an important variable in determining the interception of solar radiation and crop water transpiration, hence affecting biomass and yield accumulation. Observed LAI from the experimental site of Nanjing, China, in 2002, with irrigation and high nitrogen, was used to calibrate the LAI rate of increase. of With high nitrogen and irrigation, the LAI rate of increase is about 0.15-0.18. For most field level rice, the LAI rate of increase is less than 0.15 because of the limitations of low nitrogen and the water stress effect. There is a good agreement between observed and simulated LAI in Nanjing (Figure 8a). At the early growth stage, the LAI growth rate is relatively small, and is limited by both temperature and water stress. When LAI is greater than one, the LAI growth is only affected by water stress. In Nanjing, rice was transplanted after one month of sowing After transplantation of the rice, the LAI and root biomass suffer setback due to transplanting shock. When LAI is greater than one, the LAI increases linearly and reaches its maximum near flowering. After flowering, leaf senescence begins. The senescence rate of rice is smaller than the LAI rate of increase, and the value of the senescence rate is about 50% of the LAI growth rate. The leaf senescence rate is affected by water stress, and water stress can accelerate the senescence rate. Figure 8b shows the comparison of observed and simulated rice yield with irrigation and high nitrogen levels at Nanjing in 2002. After the grain-filling period, yield increases linearly with time. The simulated rice yield is consistent with the observed rice yield.

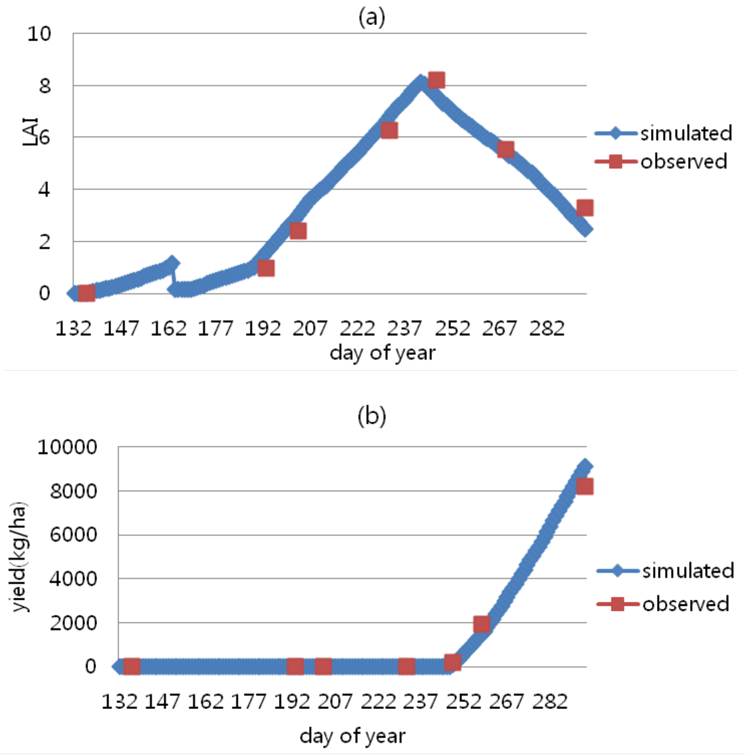

Figure 8 Calibration of GLAM-rice: (a) comparison of observed and simulated leaf area index at Nanjing, China in 2002, (b) comparison of observed and simulated rice yield at Nanjing, China in 2002.

3.2.2 Model performance at the provincial and national levels

The comparison of simulated and observed yield from 1980 to 2011 at the provincial level in South Korea is shown in Table 3. The overall simulated average rice yield at the provincial level is close to the observed yield in most of the provinces, but the standard deviation of simulated rice yield is slight higher than that of the observed yield in some provinces. This is probably because variability in simulated rice yield is only affected by climate, but the variability of observed yield is also affected by field management, policy decisions, etc. In order to adapt to sub-optimal weather conditions, a farmer can implement adaptation measures to reduce the negative impact of the environment on the crop. For example, application of organic matter in cool regions of South Korea in 1993 can alleviate the low temperature stress and greatly increase grain yield (Lee 2001).

Table 3 Comparison of observed and simulated rice yields at provincial and national level under irrigated conditions in South Korea from 1980 to 2011. RMSE: Root Mean Square Error

Name	Correlation	RMSE (kg/ha)	Observed yield (kg/ha)	Simulated yield (kg/ha)	Year
Seoul	0.41*	677	5895±474	5803±720	1980_2011
Busan	0.45**	582	5974±529	5887±587	1982_2011
Daegu	0.59**	502	6014±546	6197±504	1982_2011
Incheon	0.07	600	6187±460	6118±428	1980_2011
Gwangju	0.29	601	6340±417	6186±561	1987_2011
Daejeon	0.48*	449	6556±352	6317±487	1989_2011
Ulsan	0.78**	310	6144±398	6040±480	1998_2011
Gyeonggi_do	0.45**	670	6124±445	5979±731	1982_2011
Gangwon_do	0.70**	778	5867±766	5587±1031	1980_2011
Chungcheongbuk_do	0.63**	582	6331±608	6360±742	1980_2011
Chungcheongnam_do	0.66**	445	6741±488	6779±584	1980_2011
Jeollabuk_do	0.56**	457	6859±398	6921±541	1980_2011
Jeollanam_do	0.50**	503	6330±430	6436±551	1980_2011
Gyeongsangbuk_do	0.69**	579	6249±788	6140±632	1980_2011
Gyeongsangnam_do	0.50**	642	5993±622	5843±644	1980_2011
Jeju_do	0.49**	739	5534±625	5577±818	1980_2011
National	0.71**	405	6366±501	6342±568	1980_2011

* Correlation is significant with $P < 0.05$, ** Correlation is significant with $P < 0.01$.

In 14 out of 16 provinces/cities, there is a significant correlation between the observed and simulated yield (r = 0.41-0.78, $p < 0.05$) (Table 3). The model is unable to capture the variability in the observed rice yield only in Incheon and Gwangju. This is probably because rice yield variability at those two locations is not affected by climate variability, or the rice is not well irrigated. In GLAM-rice, rice was simulated for fully irrigated conditions. Rice is usually irrigated when the depth of the ponded water is below a critical value. Therefore, variability in simulated rice yield is mainly affected by temperature and solar radiation. There are no detailed datasets on irrigation methods and irrigation amounts for South Korea, so the accurate simulation of irrigation is impossible. In order to test the model skill at the national level, simulated provincial rice yields were aggregated to the national level by area-weighted averaging. Comparison of observed and simulated rice yield at the national level of South Korea from 1980 to 2011 is shown in Figure 9. There is good agreement between the observed and simulated rice yields at the national level (r = 0.71, $p < 0.01$). GLAM-rice can capture most of the variability in the observed yield. Rice yield is underestimated or overestimated only for some years. More detailed information on rice production and more field experiments datasets are required to further calibrate and improve GLAM-rice.

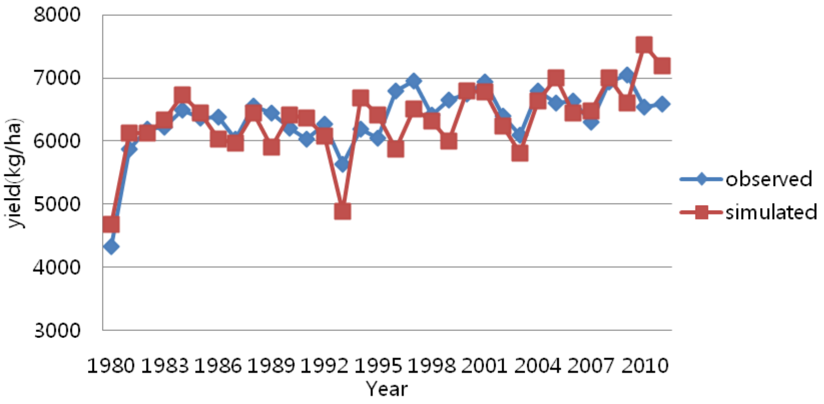

Figure 9 Comparison of observed and simulated rice yield at the national level in South Korea from 1980 to 2011(r=0.71, $p<0.01$).

3.2.3 Evaluation of CORDEX for climate impact study

In order to evaluate the reliability of CORDEX in reproducing climate variables for South Korea, seasonal temperatures from YSU-RSM, RegCM4, SNU-MM5, and HadGEM3 were compared with observed temperatures at 0.25 × 0.25 degree scale for South Korea for 2000-2005 (Figure 10). Only six years (2000-2005) of observed (2000-2010) climate data overlapped with the time series of the weather data (1980-2005). The historical climate from CORDEX-East Asia is not available after 2005, and gridded historical weather from station data is not available before 2000. Results showed that predicted temperatures from YSU-RSM have a higher correlation with observed temperatures. Predicted temperatures from HadGEM3 were very different from the observations. Generally, there was an underestimation of temperature in some grid cells for all regional models. The models' ability to reproduce interannual variability of temperatures needs to be further improved, especially for prediction of extreme climate.

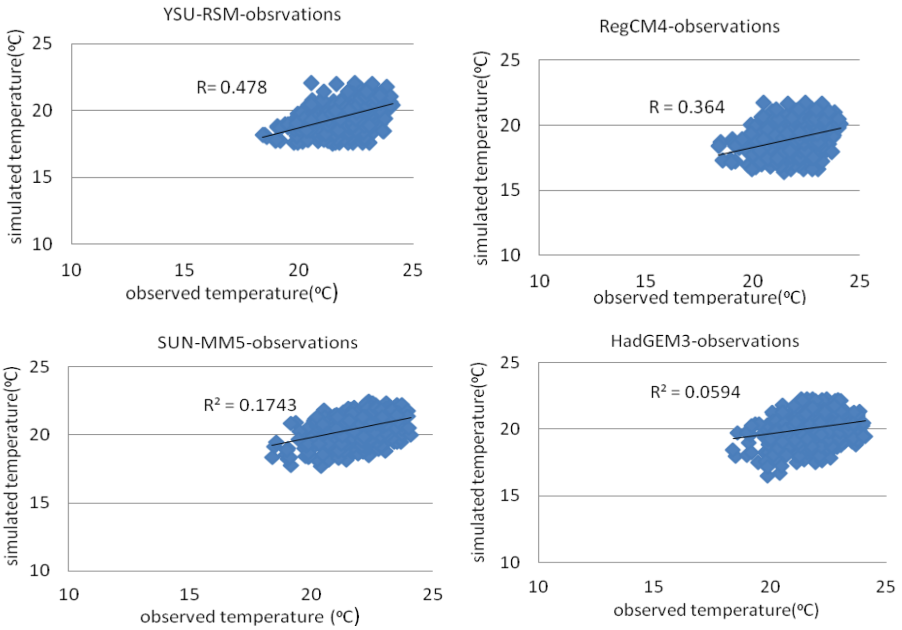

Figure 10 Scatter plot of observed seasonal mean temperature against seasonal mean predicted temperature at 0.25 × 0.25 degree scale in the main rice growing region of South Korea for 2000-2005.

To evaluate the performance of CORDEX in climate impact studies for South Korea, GLAM-rice was forced by climate variables from YSU-RSM, RegCM4, SNU-MM5, and HadGEM3 for 1991-2000. Comparison of observed and simulated rice yield at 0.25 × 0.25 degree scale for South Korea is shown in Figures 11 and 12. Results show that there was generally good agreement between the observed and simulated rice yield when GLAM-rice was forced by the output from YSU-RSM, except for overestimation of observed yield in some grid cells in 1993. YSU-RSM cannot predict the low temperature in some grid cells in 1993, so the low temperature stress on rice yield cannot be captured by the model. GLAM-rice, with forcing from YSU-RSM, can reproduce the mean observed rice yield quite well (Figure 12) and captures most of the variability of the observed rice yield (Figure 11) for 1991-2000 in South Korea. On the contrary, significant differences are found between the observed and simulated rice yield for 1991-2000 when GLAM-rice was forced by climate variables from RegCM4, SNU-MM5, and HadGEM3. YSU-RSM performed better than the other models in climate impact studies for South Korea, but its ability to reproduce extreme climate events such as low temperature needs further improvement. In the following study, YSU-RSM will be used in GLAM-rice to assess the impact of climate change on rice in South Korea.

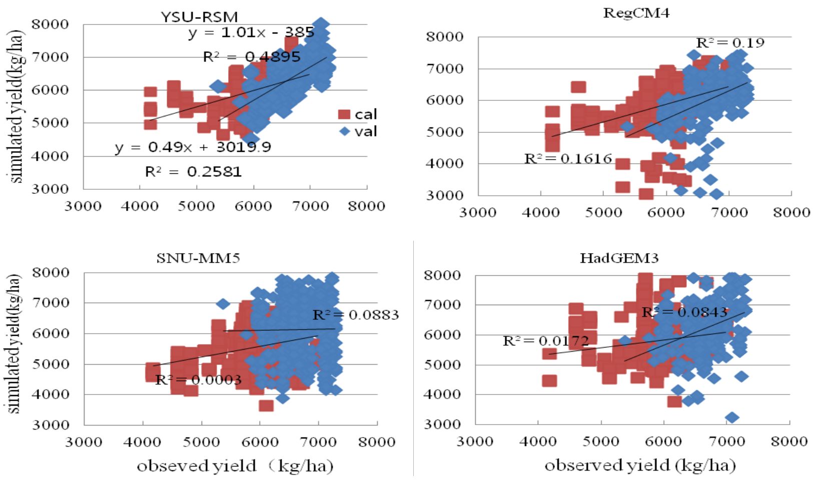

Figure 11 Scatter plot of observed rice yield against simulated rice yield at 0.25 × 0.25 degree scale in the main rice growing region of South Korea, cal: Climate variables for 1991-1995 was used to calibrate the parameters of GLAM-rice, val: the calibrated parameters for 1991-1995 was used to simulate rice yield for 1996.

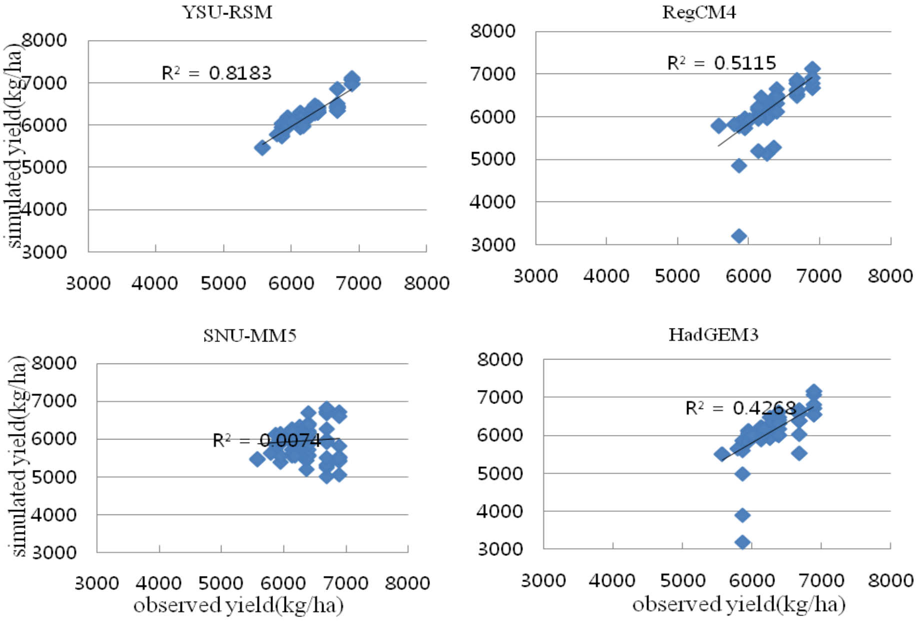

Figure 12 Scatter plot of observed average rice yield against simulated average rice yield for 1991-2000 at 0.25 × 0.25 degree scale in the main rice growing region of South Korea.

3.3 Future climate change and its impact on rice

A set of scenarios, Representative Concentration Pathways (RCPs), have been used to provide a range of possible future scenarios of atmospheric composition (Moss et al. 2008; Moss et al. 2010). The RCPs have been used by the World Climate Research Programme’s Fifth Coupled Model Intercomparison Project (CMIP5) to drive the climate model (Taylor et al. 2009). The rcp4.5 emission scenario represents a low to medium emission scenario, with stabilization from 2150 onward, and the rcp8.5 emission scenario represents a high emission scenario with stabilizing emission after 2100 (Meinshausen et al. 2011). These two emission scenarios have been used by YSU-RSM to drive the regional climate scenarios. The projected CO_2 concentration and related changes in temperature and rainfall from YSU-RSM across South Korea for 2041-2050 are summarized in Table 4. By 2050, the average seasonal temperature in South Korea's main rice growing region will increase by 2.1 and 2.7 °C relative to the baseline (1991-2000) for the rcp4.5 and rcp8.5 scenarios, respectively. For both scenarios, the model predicts an increase in rainfall for the period 2041-2050. The rcp8.5 scenario predicts a greater increase in rainfall (25.8%) than the rcp4.5 scenario (1.8%). By 2050, the predicted CO_2 concentrations will reach 487 and 541 ppm under the rcp4.5 and rcp8.5 scenarios, respectively (Meinshausen et al. 2011).

Table 4 Changes in the average climate for 2041-2050 under the rcp4.5 and rcp8.5 scenarios (from YSU-RSM) over South Korea relative to baseline (1991-2000) and corresponding CO_2 concentrations and the predicted change in the average rice yield without and with CO_2 effect during 2041 to 2050 for the rcp4.5 and rcp8.5 scenarios, relative to the baseline (1991-2000). Kolmogorov-Smirnov (KS) test was used to determine if two datasets differ significantly. The null hypothesis is rejected if there is no difference between the datasets if *P* is "small".

YSU-RSM		Climate change		Without CO_2		With CO_2	
Scenarios	CO_2 (ppm)	Changes in temperature(°C)	Changes in Rainfall (%)	Yield impact (%)	P-value	Yield impact (%)	P-value
rcp4.5	487	2.1	1.8	-5.9	p<0.001	3.5	p<0.001
rcp8.5	541	2.7	25.8	-7.6	p<0.001	5.9	p<0.001

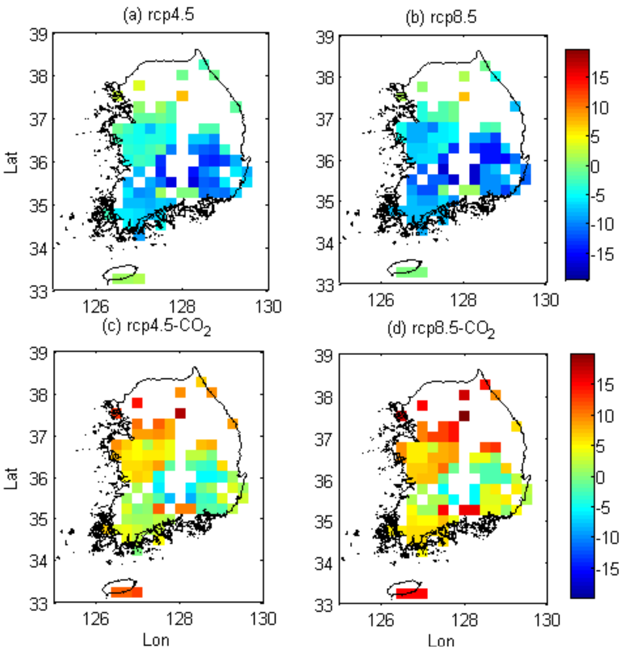

Figure 13 The predicted changes in the average rice yield without (a, b), and with (c, d) CO_2 fertilization effect from 2041 to 2050 for the rcp4.5 and rcp8.5 climate change scenarios, relative to the baseline (1991-2000). White grid cells are regions where no rice is grown.

To investigate the climate impact on rice yield in South Korea, the rice yield from 2041 to 2050 for the rcp4.5 and rcp8.5 scenarios are simulated. Figure 13 shows the predicted changes in the average rice yield from 2041 to 2050 for the rcp4.5 and rcp8.5 climate change scenarios, relative to the baseline (1991-2000). Without the CO_2 effect, rice yield from 2041 to 2050 increased slightly in some grid cells in the north of South Korea. The increase in rice yield in the north may be due in part to the shortening of the pre-flowering duration by the higher temperatures, which causes the post-flowering to begin early, which in turn causes the rice to experience a longer and cooler post-flowering stage. In contrast, yield is reduced by about 10-15% in the south. In general, without the CO_2 effect, climate change by 2050 in South Korea will result in a 5.9 and 7.7% reduction of average national rice yield for the rcp4.5 and rcp8.5 scenarios, respectively, which is significantly ($p < 0.001$) different from the baseline yield (Table 4). At the same time, rice yield variability (without the CO_2 effect, standard deviations of yield are 554 and 592 kg/ha for the rcp4.5 and rcp8.5 scenarios, respectively) by 2050 will increase compared to the baseline (standard deviation of yield is 506 kg/ha) due to increased climate variability.

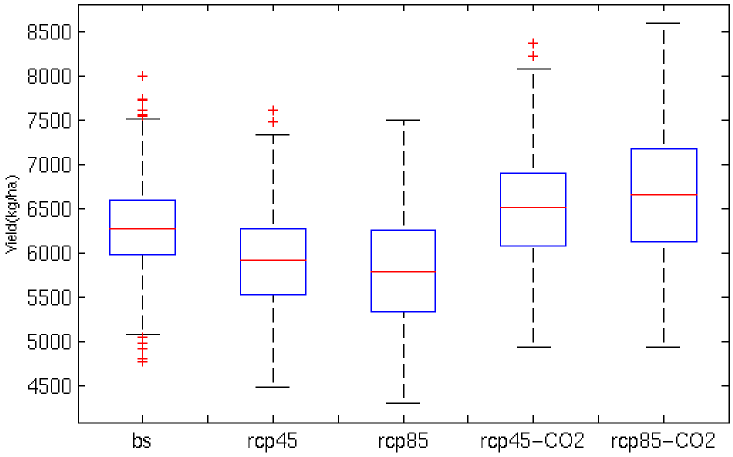

Figure 14 Comparison of simulated average rice yield in South Korea for baseline 1991-2000 (bs), and future climate scenarios (rcp4.5 and rec8.5) from 2041 to 2050, without and with CO_2 effect.

When the CO_2 fertilization effect is considered, rice yield for the rcp4.5 and rcp8.5 climate change scenarios is expected to increase in most of South Korea. Rice yield in the north would increase further with elevated CO_2 concentrations. With the CO_2 fertilization effect, the rcp4.5 and rcp8.5 climate scenarios would result in the largest increase in yield in the north. Across South Korea, the CO_2 fertilization effect would offset most of the reduction in rice yield due to warming. With CO_2, the rice yield of South Korea would increase by 3.5 and 5.9% for the rcp4.5 and rcp8.5 scenarios, respectively. The increase in yield is slightly higher under the rcp8.5 climate scenario than the rcp4.5 climate scenario due to higher CO_2 concentrations. On average, warming by 2050 could lead to a slight increase of rice yield variability (with the CO_2 effect, standards deviation of yield are 609 and 680 kg/ha for rcp4.5 and rcp8.5 scenarios, respectively) compared to the baseline (standard deviation of yield is 506 kg/ha). In the rcp8.5 scenario, variability in rice is greater than that in the rcp4.5 scenario (Figure 14).

3.4 Potential adaptation to climate change

In this study, adaptation strategies, including changes in planting dates and use of earlier/later rice maturing varieties, were tested. Rice yield was simulated by changing the planting dates by -20 and +20 days (other settings are the same as for the baseline) relative to the original baseline planting dates, with climate change conditions, including the CO_2 effect. When the planting dates were shifted earlier by 20 days, the average rice yield increased by 3.6 and 5.4% for the rcp4.5 and rcp8.5 scenarios, respectively, (Table 5) by 2050. In contrast, shifting the planting dates 20 days later results in a large reduction in rice yield for both the rcp4.5 and rcp8.5 scenarios (Figure 15). Changes in the planting dates can alter seasonal climate conditions. Planting crops earlier can cause crops to develop earlier, so the crops experience cooler climates during the grain-filing period, consequently increasing yield. Shifting planting dates earlier has a small beneficial impact on rice yield in South Korea.

Table 5 The predicted change in the average rice yield with CO_2 and adaptation during 2041 to 2050 compared with average rice yield with CO_2 and without adaptation for the rcp4.5 and rcp8.5 scenarios in South Korea.

Adaptation	Scenarios	rcp4.5	rcp8.5
Adaptation impact on yield (%)	Planting -20	+3.6	+5.4
	Planting +20	-7.1	-10.2
Adaptation impact on yield (%)	Earlier maturing	-17.3	-16.3
	Later maturing	+16.9	+16.1

The possible impact on rice yield of using earlier and later maturing rice varieties is shown in Table 5. Rice yield was simulated by changing only the rice maturing varieties (other settings remain the same as for the baseline) with future climate change conditions, including the CO_2 effect. Changes in rice maturing varieties showed a similar pattern for the rcp4.5 and rcp8.5 climate scenarios from 2041 to 2050. Using an earlier maturing rice variety can lead to 17.3 and 16.3% reduction in rice yield for the rcp4.5 and rcp8.5 climate scenarios, respectively. In contrast, using a later maturing rice variety for the rcp4.5 and rcp8.5 climate scenarios results in an increase in rice yield of 16.9 and 16.1% for the rcp4.5 and rcp8.5 scenarios, respectively. Rice yield can thus be improved by using a later maturing rice variety (Figure 15).

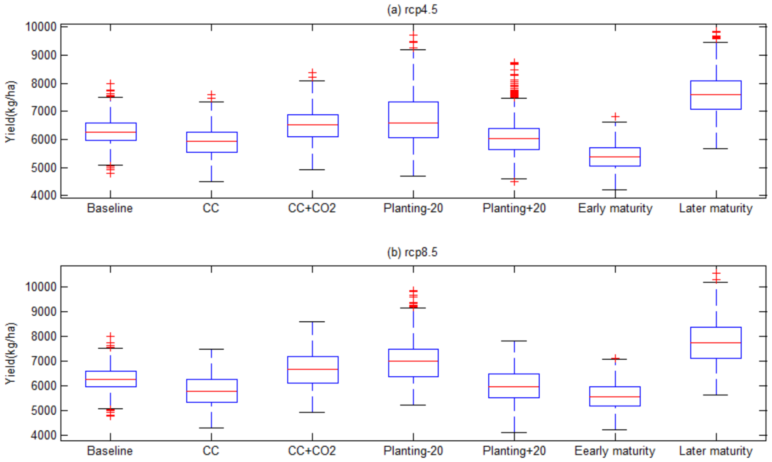

Figure 15 Comparison of average rice yield for baseline (1991-2000) and future climate scenarios (rcp4.5 and rcp8.5) without and with adaptation from 2041 to 2050 in South Korea, CC: climate change only; CC+CO_2: climate change with CO_2 effect; planting-20: shifting planting data 20 days early relative to baseline; planting-20: shifting planting data 20 days later relative to baseline; early (later) maturity: use of early and later maturing rice varieties. All adaptation is simulated under future climate change condition with CO_2 effect.

4. CONCLUDING REMARKS

Rice is the largest crop in South Korea. After 1988, there was a decreasing trend in rice production, mainly due to a reduction in the rice harvest area. Rice yield anomalies did not show significant correlation with seasonal total rainfall because rice is irrigated in most of South Korea. In contrast, the current warming trend has a positive impact on rice yield in South Korea. Variability in rice yield in South Korea is partly determined by temperature variability. Low temperature is one of the limiting factors affecting rice production. Some measures, such as using cold tolerant varieties, transplanting earlier, and increasing the temperature of the irrigation water can improve the cold tolerance of rice and alleviate cold stress. Real-time seasonal rice forecasts are necessary to help farmers improve decision making and manage risk in advance.

Based on the existing GLAM-wheat framework, a large area rice model was developed by modifying some model parameters, and defining the rice development and growth processes (Figure 2). The GLAM-rice development processes includes: collecting the rice growth and development parameter sets from the literature and experimental data, incorporating the soil water balance in paddy rice fields from ORYZA2000 into GLAM, defining the leaf area growth of rice, considering the effect of the photoperiod and its interaction with temperature on the development of rice, quantifying the impact of high/low temperatures on rice, and parameterizing the CO_2 fertilization effect on rice growth. Simulated and observed yields were compared at the provincial level of South Korea to evaluate the performance of GLAM-rice. In general, GLAM-rice can simulate the average rice yield well at the provincial level, and can capture a large part of the observed rice yield variability at the provincial level, but GLAM-rice needs to be further validated for various climate conditions.

In GLAM, crop yield loss due to nutrients, pests, disease, and field management is not directly modeled, but is represented by the yield gap parameter, which allows the model to focus on the response of crop yield to spatial and temporal weather and climate variability. GLAM has the benefit of low input data requirements, validity over large areas, and the potential to capture variability due to different sub-seasonal weather patterns (Challinor et al. 2004). The simplified model formulation means fewer crop parameters are needed, and the model can be operated at a relatively large spatial scale. The regional rice model GLAM-rice can be transferred to APCC (APEC Climate Center) product users/stakeholders for regional rice forecasting and climate change impact assessments at large spatial scales. Some simple assumptions and empirical relationships were applied in GLAM to predict complex crop growth and development. The response of rice to extreme events such as frost, hail, and flooding is not included in the model. In future climate conditions, the frequency of extreme climate events is likely to increase, resulting in increased risk of crop damage. Thus, the response rice growth and development to extreme climate events will need to be further developed and improved.

To evaluate the performance of CORDEX in climate impact studies for South Korea, GLAM-rice was forced by climate variables from YSU-RSM, RegCM4, SNU-MM5, and HadGEM3 for 1991-2000. Results showed that there was generally good agreement between observed and simulated rice yield when GLAM-rice was forced by the output from YSU-RSM, but not when forced by the other models. Therefore, YSU-RSM outputs were used in GLAM-rice to assess the impact of climate change on rice in South Korea. Accuracy of the weather data inputs to the crop model is a prerequisite for confident yield prediction, so the climate models' ability to reproduce extreme climate events such as low temperatures needs to be further improved.

YSU-RSM predicted a 2.1 and 2.7°C increase in seasonal mean temperatures by 2050 for the rcp4.5 and rcp8.5 scenarios, respectively. The model also predicted an increase of rainfall by 25.8% for the rcp8.5 scenario, and a minor increase (1.8%) in rainfall for the rcp4.5 scenario. Without the CO_2 effect, climate change will result in 5.9 and 7.7% reduction of rice yield by 2050 in South Korea in the rcp4.5 and rcp8.5 scenarios, respectively. With the CO_2 fertilization effect, the rice yield would increase by 3.5 and 5.9% for the rcp4.5 and rcp 8.5 scenarios, respectively. The negative impact of climate change on rice can be offset by the CO_2 fertilization effect. By 2050, warming could lead to a slight increase in rice yield variability, consistent with the results of Kim and Pang (2000), who reported that variability in rice yield variability might increase by up to 10%-20% due to climate change. Crop yield and crop yield variability are two of the crucial criteria for sustainable land management

(Smyth and Dumanski 1993). Mean yields show the average level of productivity. Yield trends and yield variability are also essential to examine whether crop yield and yield risk are stable, enhancing, or declining over time (De Jong and Stewart 1997). It is important to provide early warning to help manage risk in order to maintain the stability of rice yield.

Table 6 Studies on the impacts of climate change on rice yield in South Korea.

period	Climate scenarios	Yield impact (%)	Without/with CO_2	Crop model	References
2025s 2055s 2080s	A1B	-0.4 3.9 17.5	with CO_2	CERES-Rice	Lee et al. 2012a
2055S	A1B	0.9(early-maturity) -2.5(mid-maturity)	with CO_2	ORYZA2000	Lee et al. 2012b
2040s	A1B rcp8.5	-3 -7	with CO_2	CERES-Rice	Kim et al. 2012
2050s	GCM-mm^5	55	with CO_2	AquaCrop	Chung, Sang-Ok 2010
	+2°C 1.5×CO2 +2°C	-10.8 to -19.7 0.4 to 5.4	without CO_2 with CO_2	ORYZA2000	Shin 1995
2041-2050	rcp4.5 rcp8.5 rcp4.5 rcp8.5	-5.9 -7.7 3.5 5.9	without CO_2 with CO_2	GLAM-rice	This study

Studies on the impact of climate change on rice yield for South Korea are shown in Table 6. A direct comparison is impossible due to differences in the projected climate scenarios, crop simulation methods, time periods, and spatial scales among these impact assessment studies. However, they are consistent in that without the CO_2 fertilization effect, medium- to long-term climate change would have a negative impact on the rice yield of South Korea. Except for the study by Kim et al. (2012), most of these studies showed that the negative impact of climate change is likely to be offset by the CO_2 effect. However, different studies report different magnitudes of changes in rice yield in response to climate change. Sang-Ok (2010) reported a greater increase in rice yield (55%) in South Korea for the 2050s, while Kim (2012) showed that climate change with the CO_2 effect would result in a small reduction in rice yield during the 2040s. This predicted change in rice yield from GLAM-rice is comparable to simulation studies from Lee et al. (2012a), Lee et al. (2012b), and

Shin (1995). The great uncertainty in the response of rice to climate change is probably caused by the uncertainties in the climate change scenarios projected by different climate models. The uncertainties of the projected climate change scenarios arise from (1) the uncertainty in future greenhouse gas emissions, (2) regional climate models themselves, and the lateral boundary provided by GCM, and (3) the uncertainty in the natural variability of the climate system. Continued assessments of climate impact with different climate change projections from different climate models are clearly needed.

In this study, adaptation strategies, including changes in planting dates and in the use of earlier and later maturing varieties of rice, were tested to improve rice yield. When the planting dates were shifted earlier by 20 days, the average rice yield increased by 3.6 and 5.4% for rcp4.5 and rcp8.5 scenarios, respectively. This result is consistent with the findings of Kim (2013), whose results from CEREC-rice showed that shifting the planting date 14 days earlier can increase rice yield by 1.1 and 3.5% for the mid-maturity and early maturity varieties, respectively, under projected future climates for 2031-2060 in South Korea. Using a later maturing rice variety can lead to 16.9 and 16.1% increase in rice yield for the rcp4.5 and rcp8.5 climate scenarios, respectively. To improve rice yield and meet future food demands, alternative options for rice crop adaptation, such as using tolerant varieties, expansion of agriculture, and the support of government policies, remain necessary for South Korea. With adaption, rice yield may increase slightly in future climates. However, even if total rice production increases, it may still be insufficient to meet the requirement of an increasing population. The goal of the South Korean government is to achieve food sovereignty (Yoon et al. 2013), thus increasing total grain production and maintaining food security is a critical issue.

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