Climate change model predicts 33 % rice yield decrease in 2100 in Bangladesh

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RESEARCH ARTICLE

Climate change model predicts 33 % rice yield decrease in 2100 in Bangladesh

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Abstract In Bangladesh, projected climate change is expected to increase food demands by more frequent and intense droughts and increasing temperatures. Few investigations have studied the impact of climate variability on future rice production. Previous investigations mainly checked the sensitivity of higher air temperature and higher atmospheric carbon dioxide on rice yields. Whereas in this study, we checked the combined effects of major climatic parameters on rice. The effects of climate change on yield of a popular winter rice cultivar in Bangladesh were assessed using the biophysical simulation model ORYZA2000. This model was first validated for 2000–2008 using field experimental data from Bangladesh, with a careful test of climate data on daily basis for station-wise and reanalysis datasets. The model performance was satisfactory enough to represent crop productions in nine major rice-growing districts. Then, simulation experiments were carried out for 2046–2065 and 2081–2100. Results show 33 % reduction of average rice yields for 2046–2065 and 2081–2100 for three locations. Projected rainfall pattern and distribution will also have a negative impact on the yields by increasing water demands by 14 % in the future. The model also showed that later transplanting will have less damage under the projected climate.

Keywords Climate · Rice · Temperature · Rainfall · Yield · Bangladesh

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1 Introduction

Bangladesh is the world's fourth largest rice-producing country, with an area of about 11.54 million ha for rice cultivation. The contribution of rice alone to the total cereal production of the country is about 95.4 % (BBS 2006). Traditionally, rice has been the staple food, and about 70 % of the country's cultivable land is under rice cultivation. In Bangladesh, rice is grown in three seasons locally named aus (summer), aman (monsoon), and boro (winter). Summer, monsoon, and winter rice are grown during April to August, July to December, and December to May, respectively. The major rice crop boro is transplanted in winter and facing high temperature in summer at its reproductive stages. It will be more affected with increased temperature in the future. Crop failure due to either drought or excess rainfall is already putting a significant strain on the socioeconomic structure of Bangladesh and will be more severe in the future.

The country has a humid, warm, tropical climate with six seasons. Among the seasons, summer, monsoon and winter are prominent. Winter (December through February) is relatively cooler and drier with the average minimum temperature in the range of 7.2–12.8°C and the maximum of 23.9–31.1°C. Warm conditions generally prevail throughout the monsoon season, although cooler days are also observed during and following heavy downpours. Summer is hot with an average maximum of 36.7°C and the peak of the maximum temperatures is observed in April.

Like as many other parts of the world, clear observations of changes in temperature and rainfall are evident in Bangladesh. For example, Islam (2009) reported that in Bangladesh mean temperatures have risen by about 1°C over the past half-century while a number of studies (e.g., Choudhury et al. 1997; Quadir et al. 2003) reported the changing trend of rainfall for the recent decades. Bangladesh is highly vulnerable to climatic events, especially to floods and droughts. During the past 50 years, Bangladesh experienced about 20 droughts (National Encyclopedia of Bangladesh 2012). In certain years, the damage caused by rainfall deficit was greater than that due to flooding. In 1982, drought caused a total loss amounting to about 53,000 tons of rice, compared with 36,000 tons lost due to flood damage (Ramasamy and Baas 2007). Floods caused yield losses almost every year in some parts of Bangladesh. Although in winter, effects of flood were not so significant, but they still accounted for a loss of 10 % of the total loss (caused by flood) during the period from 1974–1975 to 1998–1999.

Variability of temperature and rainfall during the life cycle of rice has observable phenological impacts. Yoshida (1981) showed that rice suffered from heat damage when it was exposed to air temperatures above 35°C. Islam (2011) reported decreased grain yields in rice with high temperature (34°C) at grain-filling stages. The timing of rainfall onset and the duration are also crucial factors for rice cultivation in Bangladesh. Islam et al. (2002) showed that the interannual variation in crop yield was mainly due to the variation in the amount and distribution of rainfall throughout the crop's life cycle. Water stress during the vegetative stage delayed leaf emergence, reduced leaf area expansion and partitioning, and thus reduced the assimilate source (Wopereis 1993). Water deficit particularly at grain-filling stages significantly reduced rice yields (Islam 2010).

Global warming poses a threat dependent on its magnitude to human society by changing the agro-environment and agriculture. For Bangladesh, Agrawala et al. (2003) showed increases of 1.1, 1.6, and 2.7°C of winter temperature (December to February) for the years of 2030, 2050, and 2070, respectively, while rainfall is projected to decrease by 1.2, 1.7, and 3.0 % for the same corresponding years. Advanced general circulation models such as those from the Canadian Climate Center, the Geophysical Fluid Dynamics Laboratory, and the United Kingdom Meteorological office estimated increases of 2–4, 4–6, and 2–4°C, respectively, in the winter season air temperature in Bangladesh for the doubling of carbon dioxide (Mitchell et al. 1990). In the same study, a 1 mm day^{-1} decrease in precipitation (to 2 mm day^{-1}) was predicted. The magnitude of the change in climate would be a great concern for the future. Despite the uncertainties in the general circulation model's predictions, their prognostications are still significant for climate change impact studies (Ghan 1992).

In Bangladesh, during 2007–2008, winter rice production contributed 58.4 % to the total rice production, while monsoon and summer rice were accounted for only 34 and 7 %, respectively (BBS 2009). Such contribution of winter rice, along with very significant rising trend (0.37 million tons year$^{-1)}$ during 1971–2005, showed the immense importance of winter rice in Bangladesh. However, with increases in minimum and maximum daily temperatures in the future, the rice is expected to be declined. Basak (2010) stated that Bangladesh rice shortage may turn to 50 % in combination with high population and temperature rise in 2050. The current scenario of shortage rice production in Bangladesh (around 2.5 million tons during 2006–2007) would be more crucial in the future due to pressure from rapid population growth and associated climate change impact.

Since crop culture, which is associated with land-based and biomass-producing activities, will likely be the most affected sector due to climate change, measures should be adopted to overcome the adverse effects and to achieve higher production. It is therefore utmost urgent to understand the crop–climate relationship from the recent interannual variability and illustrate future scenarios. Actions should be taken bearing the situation of limited irrigation facilities, changing rainfall patterns and distribution, in addition to warming. Although some simulation studies have been carried out to assess climate change impacts on rice yields in Bangladesh (Basak et al. 2010; Karim et al. 1996; Mahmood et al. 2003), few studies have focused on future scenarios. Previous works mainly highlighted the effects of higher air temperature and higher atmospheric carbon dioxide on crop yields; while an attempt was made in the current study to find the combined effects of all major climatic parameters in climate change.

The present study considered the possible impacts of climate change on a high yielding modern rice variety BRRI dhan29, most important economically. The variety is released by Bangladesh Rice Research Institute and suggested for winter cropping. Having similar life cycles, this cultivar produces higher grain yield than any other rice varieties currently being cultivated in winter. The main purpose of the present study is to investigate the water-limited rice yields in Bangladesh for a changed climate. Rice production was estimated across three selected districts with different planting dates and periods by using a crop simulation model ORYZA2000. A case study was carried out to find out the optimum planting date for the variety. Furthermore, the regions that are most vulnerable to extreme climatic events were determined. Measures that can be applied in such regions to overcome the extreme climatic problems would be the important outcome of this study.

Another benefit of ORYZA2000 is the saving of time through avoiding time-consuming field experiments. In Section 2, datasets are introduced and the description, calibration, and evaluation procedure of the model ORYZA2000 are presented. The results of the calibration and evaluation are given first in Section 3, and then, the effects of future climate change on the studied rice cultivar are reported next. These results and the implication for the future trends are discussed in Section 4.

2 Data and methods

2.1 Soil, crop management, study sites, and rice production data

Data on soil characteristics, such as texture, number of soil layers and depth of each layer, organic matter (in percent), percolation rate (in millimeters per day), groundwater table depth (in centimeters), etc., were collected from the Soil Resources Development Institute, Bangladesh. Table 1 shows the data for the experimental site. The loamy soil contained organic matter as 1.54 % at the uppermost layers, while the bulk density was almost the same at all layers (Soil Resources Development Institute, Reconnaissance survey 1975 and semi-detailed survey 1984–2002). Van Genuchten parameters (α, β, l, and n) showed a little variation between layers. Hydraulic conductivity (K_{sat}) was higher for the second and third uppermost soil layer, whereas water content at saturation (θ_s) was almost same for different layers.

Recommended agronomic practices for the rice cultivar were followed for all the model simulations and also for the field trial (BRRI 2007). Farm-level data on rice yield (in tons per hectare) were collected from the publications of Bangladesh Rice Research Institute during the time span 2000–2001 to 2007–2008. Nine major rice-growing districts, representing four regions of Bangladesh, were selected for the simulation of potential rice yields during 2000–2008 by using the hind-casted climate data (Table 2). Reanalyzed data were used only for six available districts for the same time span. Depending on projection data availability, three districts, named as Rangpur, Faridpur, and Barisal, were selected for future yield simulation.

2.2 Climate data

Climate parameters contained mean values of maximum and minimum surface air temperatures (in degrees Celsius), total rainfall (in millimeters), radiation (sunshine hours or kilojoules per square meter per day), mean wind speed (in meters per second), and maximum and minimum humidity (in percent; for getting vapor pressure), all on a daily basis. In the present study, simulations for observed rice yields were also done with the use of daily reanalysis data from National Centers for Environmental Prediction (2.5×2.5° resolution) and Asian Precipitation Highly Resolved Observational Data Integration Towards Evaluation of the Water Resources (0.25×0.25° resolution). Depending on data availability and the nearest grid locations to the stations, ORYZA2000 used projected climate data, generated by the Geophysical Fluid Dynamics Laboratory—Climate Model 2.1, USA with A2 Intergovernmental Panel on Climate Change-Special Report on Emissions Scenarios for Rangpur and Faridpur. The data generated by the model from Meteorological Research Institute-Coupled Global Climate Model 2.3.2, Japan with A1B scenario was used for illustration of future rice production in Barisal. The first climate model having 2.5×2° resolution with A2 scenario was chosen assuming a world with less technological advancement,

Table 1 Soil properties and Van Genuchten parameters for loamy soil texture at experimental site

Soil depth (cm)	SOM (%)	BD (g cm^{-3})	PERC (mm day^{-1})	Sand (%)	Silt (%)	Clay (%)	K_{sat} (cm day^{-1})	θs (cm^3 cm^{-3})	VGA (cm^{-1})	VGL (−)	VGN (−)	VGR (cm^3 cm^{-3})
0–9	1.54	1.47	5	32	56	12	3.89	0.43	3.42	−0.39	0.32	0.16
9–15	1.42	1.43	NA	30	55	15	4.07	0.44	3.26	−0.49	0.38	0.17
15–30	1.06	1.41	NA	26	58	16	4.02	0.45	3.03	−0.51	0.39	0.17
30–50	0.84	1.43	NA	23	63	14	3.91	0.44	2.96	−0.49	0.34	0.16

$S=(\theta-\mathrm{VGR})/(\theta s-\mathrm{VGR})=1/[1+(\mathrm{VGA}\ h)^{\mathrm{VGN}}]^m$

$K(S)=K_{sat}\ S^{\mathrm{VGL}}\ [1-(1-S^{1/m})^m]^2$

Source: Genuchten (1980)

S degree of saturation (−); *SOM* soil organic matter; *BD* bulk density; *PERC* percolation; *NA* not applicable; θ_s saturated values of volumetric water content (in cubic centimeters per cubic centimeter); *h* soil pressure head (in centimeters), *m* 1−1/VGN; K_{sat} saturated hydraulic conductivity (in centimeters per day); *VGA* Van Genuchten alpha parameter (in centimeter); *VGL* Van Genuchten lambda parameter (−); *VGN* Van Genuchten *n* parameter (−); *VGR* Van Genuchten residual water content (in cubic centimeters per cubic centimeter)

Table 2 Yields (in tons per hectare) of the studied rice cultivar over 2000–2001 to 2007–2008 at nine districts of Bangladesh

Districts	Average potential yields (tons ha^{-1})		
	Sation[a]	Reanalyzed[b]	Field[c]
Rangpur	8.14	NA	7.66
Rajshahi	8.24	7.87	7.46
Gazipur	8.13	8.12	7.12
Faridpur	8.23	NA	7.78
Habigonj	7.31	7.26	6.68
Feni	7.21	7.57	6.22
Comilla	7.86	8.03	7.07
Satkhira	7.11	NA	6.44
Barisal	6.96	7.38	6.26

NA not available for lack of reanalyzed climate data

[a] Simulated values by meteorological stations hind-casted data

[b] Simulated values by reanalysis climatic data

[c] Observed yield at field level

while the later one ran with 2.75×2.5° resolution and A1B scenario was considered as a balanced one. With the output of both climate models, rice production was projected over the time spells 2046–2065 and 2081–2100. Predictions were done considering the increases in atmospheric carbon dioxide as 1.9 ppm $year^{-1}$ starting from 358 ppm at 1994 (Intergovernmental Panel on Climate Change Assessment Report 3 and 4). Predicted temperature for winter rice-growing season (December to May) during 2046–2065 is presented in Fig. 1 for overall Bangladesh.

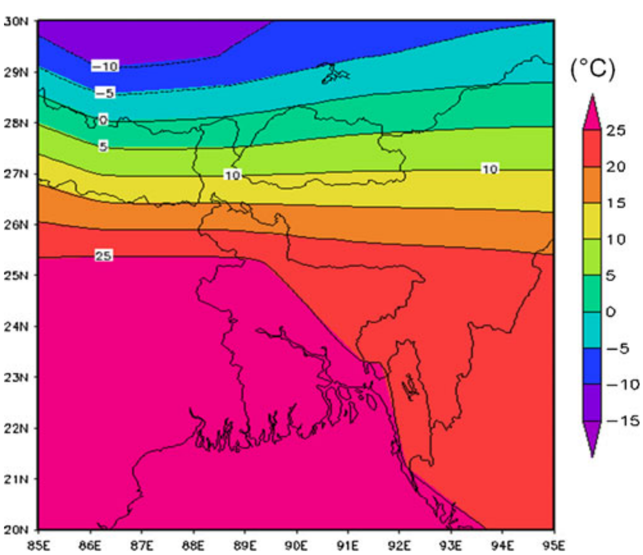

Fig. 1 Predicted seasonal average air temperature (in degrees Celsius) in Bangladesh during 2046–2065, generated by Geophysical Fluid Dynamics Laboratory 2.1

2.3 Model description of ORYZA2000

ORYZA2000 is an advanced, dynamic ecophysiological rice growth simulation model. Considering the situation of potential, water limitation, and nitrogen limitation, the model is able to estimate yields of irrigated and rain-fed rice and to determine duration of growth stages, dry matter production and partitioning, soil water balance, etc. The control of diseases, pests, and weeds is assumed to be optimal in this model. This model has been widely applied to understand the relationship between rice and diverse weather conditions (Jing et al. 2007; Bouman et al. 2007). The performance of the model was also found to be satisfactory and acceptable through recent validation under different water regimes, irrigation practices, and various levels of nitrogen fertilization with 1 day time step (Boling et al. 2007; Feng et al. 2007). A detailed explanation of the model is given by Bouman et al. (2001) and Bouman and Van Laar (2006).

The model describes four key development stages, such as emergence, panicle initiation, flowering, and physiological maturity. For completion of each phase, development days are given as variety-specific constant numbers, and the phases are linearly related with a daily mean temperature, ranging from a base of 8°C to an optimum of 30°C and maximum at 42°C. The model integration includes the calculation of light profile within the canopy from the amount and vertical distribution of leaf surface area. The daily canopy assimilation rate is found by integrating the instantaneous leaf photosynthesis rate over the height of the canopy within the day. Gross photosynthesis of individual leaves is calculated by a negative exponential function characterized by the initial slope and an asymptote (Eq. 1). The maximum rate of carbon dioxide assimilation of a leaf (A_m) is calculated from the N content of the leaves and average day time temperature.

$$A_1 = A_m[1 - \exp(-eI_a/A_m)] \quad (1)$$

where A_1 is the gross assimilation rate, A_m is the gross assimilation rate at light saturation, e is the initial light use efficiency, and I_a is the amount of absorbed radiation.

The daily net assimilation is obtained by subtraction of growth and maintenance respiration from the daily gross assimilation. The produced assimilate is partitioned among different plant organs as a function of phenological development, controlled by ambient average air temperature. The relation between average air temperature (T_{av}) and maintenance respiration is simulated by Eq. 2

$$R_m = R_{mr} \times 2^{(T_{av} - T_r)/10} \quad (2)$$

where R_{mr} is the reference maintenance respiration, and T_r is a reference temperature, 25°C.

Soil nitrogen available for daily uptake is calculated by the model using a record of nitrogen in a single soil compartment. Residual soil N and supplied fertilizers are the main sources for plant nitrogen uptake. By subtracting the actual nitrogen content of the plant from the maximum, the demand of daily crop nitrogen is estimated. The acquired leaf nitrogen concentration affects the rate of photosynthesis, development, root/shoot ratio, and senescence. However, the total amount of nitrogen in the crop affects the death rate of leaves after flowering.

Water stress factors are calculated as functions of soil water tension in the root zone. The module PADDY (Bouman and Tuong 2001; Wopereis et al. 1996) is used in the crop model to compute the vertical flows of water in and out of each soil layer on a daily basis. Water balance parameters are estimated using Eq. 3 in the model:

$$\sum [I + R + C] = \sum (E + T + P + D) + \mathrm{d}T, \qquad (3)$$

where I is irrigation, R is rainfall, C is capillary rise, E is evaporation, T is transpiration, P is percolation, and D is runoff (all in millimeters per day); dT denotes change in field water storage.

The model calculates the potential evapotranspiration (ET_o) using the Penman–Monteith equations predicting evapotranspiration from a hypothetical short grass with a height of 0.12 m. Actual transpiration is calculated from potential values by multiplication with the relative transpiration rate. For saturation soil in the surface, actual evaporation rates are equal to the potential rates, while in the absence of saturation, the evaporation rate drops from potential values proportional to the square root of time.

The module PADDY is also used for representing soil characteristics. A lowland rice soil is modeled considering a layer of muddy topsoil overlying 3–5 cm compacted soil layer and non-puddled subsoil. In case of water logging condition, vertical water flow is considered either a fixed percolation or is calculated from hydraulic conductivity characteristics of the compacted soil layer and the non-puddled subsoil. In absence of water logging, inflow water is redistributed by calculating gain and loss values for all the soil layers. Total volume of water in excess to field capacity is drained out with the maximum rate of saturated hydraulic conductivity. Van Genuchten equations are used to describe the soil water retention and conductivity characteristics in the PADDY water balance module (Genuchten 1980). The Van Genuchten parameters (α, β, l, and n) used in the soil module PADDY are calculated using the pedotransfer functions developed by Wolsten et al. (2001), with the use of available soil texture (in percent) and soil organic matter (in percent) data at the sites.

2.4 Calibration and evaluation of the model

For the studied rice cultivar, the model was calibrated first with the standard parameters of rice variety IR72. Measured data of crop variables from a field experiment in Bangladesh were also used for calibration. Development rates were calculated first using the observed dates of emergence, panicle initiation, flowering, and physiological maturity, where the corresponding dates were December 31, 2010, March 28, April 29, and June 1, 2011, respectively. Specific leaf area was calculated next from the measured values of leaf surface area and leaf dry weight. The partitioning of assimilates was derived from the measured values of leaf biomass, stem, and panicles. Then, the model was fine-tuned for having the best agreement between simulation and observation. The leaf stress parameters parameterized by Wopereis et al. (1996) were used for the rice cultivar, and other crop parameters just followed the values of the standard crop data file IR72. Calibrated parameters, such as leaf area index, total aboveground dry matter, green leaves, and panicles are shown in Fig. 2.

During the growing season, crop samples of ten hills were taken to measure the leaf area index and dry biomass, while, at maturity, grains also from ten hills were harvested to determine yield at 14 % moisture level. Capability of soil to provide residual nitrogen was considered as 0.8 kg N ha^{-1} day^{-1} (BRRI 2006). Irrigated water was recorded keeping the daily balance of a reservoir after water was supplied. Daily climate data for the major parameters were collected from the nearby meteorological station, from November 2010 to May 2011.

For the evaluation of ORYZA2000, graphical comparisons were performed between the values of simulated and measured leaf area index, biomass, and yield from the field experiment. However, statistical comparisons were made only for the yields, due to lack of leaf area index and biomass data from farm level for several years. The slope

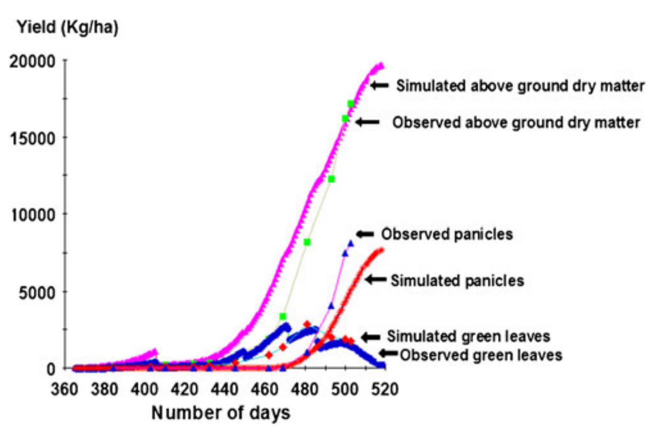

Fig. 2 Simulated and measured weight of total aboveground dry matter, green leaves, and panicles for the studied rice cultivar

(α), intercept (β), and coefficient of determination (R^2) of the linear regressions were calculated between model yields (y; obtained using hind-casted climate data) and farm-level yields (x). Moreover, Student's t test of means [p (t*)] was carried out, and the absolute root mean square error ($RMSE_a$) and normalized root mean square error ($RMSE_n$) root mean square errors between x and y were calculated (Eqs. 4 and 5) and compared with the standard errors and coefficient of variation of farm-level values.

$$\mathrm{RMSE_a} = \left[\frac{1}{n}\sum (Y_i - X_i)^2\right]^{0.5} \quad (4)$$

$$\mathrm{RMSE}_n = 100 \times \frac{\left[(1/n)\sum (Y_\mathrm{i} - X_\mathrm{i})^2\right]^{0.5}}{\sum X\mathrm{i}/n} \quad (5)$$

where n is number of observations, X_i is simulated values, and Y_i is field-level values.

3 Results and discussions

3.1 Calibration of the model

The field experiment was carried out for the requirement of calibration procedure of the model. Results shown by the graphical comparison between measured and simulated crop variables (Fig. 2) indicated that simulated values were reproduced quite well. For the field trial, values of leaf area index seemed to be lower at early stage of vegetative growth, while at flowering, it was quite higher. Variation in early stage might result due to uncalibrated relative leaf growth rate, in addition to measurement errors in the later part. A high frequency of leaf area index measurement from emergence to leaf area index=1 is suggested for accurate calculation of relative leaf growth rate. In the field trial, lack of enough measurements to calculate the relative leaf growth rate might influence the variation in leaf area index. The weights of total aboveground biomass and dry weight of green leaves were simulated pretty well, especially at the later part of crop growth. However, the measured panicles were considerably higher than the simulation, which may have been caused by overestimation. After calibration, the model simulated yields of the rice cultivar was 8.03 tons ha^{-1} compared well with the experimental yields of 7.75 tons ha^{-1}. However, in the field water, input of 950 mm was higher, as demanded by more permeable soil with a moderate groundwater table depth (200–300 cm), compared to the model simulation of 700 mm.

Despite some limitations of under- and overestimation, overall graphical comparison confirmed the models' ability to represent the current trend of rice production in Bangladesh, besides extrapolating future scenarios. However, in running the model, errors may happen for using inaccurate data format, missing values or use of inappropriate values, etc. At the time of parameterization, errors may also come from the wrong measured values. Simulation both for water- and nitrogen-limited conditions simultaneously will give errors and attention needs to be given to that.

3.2 Yield and maturity (field versus simulation)

The simulated grain yield of the rice cultivar during 2000–2008 was generally in the same order as that of field level. Using the hind-casted climate data, the model simulated the average potential yield as 7.7 tons ha^{-1} during 2000–2001 to 2007–2008 across nine rice-growing districts in Bangladesh (Table 2). At the same period with reanalyzed data, the yield simulated for six districts was 7.94 tons ha^{-1}. In contrast to the simulation, the value obtained from field production was 6.97 and 7.56 tons ha^{-1}, respectively, averaged for the nine and six districts. Observed marginal yield variations between simulation and real field at different districts in different years were probably for the adoption of optimum pest control strategy by the model; whether in the real field, some crop is lost by the pest and diseases. In spite of the variation in yields, still the relation between values simulated by station climate and field was strongly significant at 0.001 confidence level. For the relation of field data and reanalyzed simulation, it was significant at the 0.1 level. The above-mentioned data strongly correlated relations proved the model's capability to represent the field scenario in Bangladesh.

3.3 Evaluation for three selected districts

Among the districts studied before, a statistical comparison was done only for the districts named Rangpur, Faridpur, and Barisal. These districts were preferably selected for future simulation. Results showed that the agreement between simulated and farm-level yields of the rice cultivar was strong enough in all the districts. The values of R^2 were quite higher, ranging from 0.02 to 0.56 and were found highly significant for Rangpur and Barisal ($p<0.05$). Since the field experiments were conducted in diverse agro-climatic environment for eight different years and the model mostly reflected the influence of climatic parameters, some deviations were noticed between the yields. The slope α was quite close to 1, while the intercept β deviated more from 0. Yields of the studied rice cultivar obtained by model simulation and field were not significantly different with the Student's t test. For the districts Rangpur and Faridpur, values of the absolute root mean square error were quite smaller and the trend was similar to that of standard errors. However, the normalized root mean square error was found to be relatively high as 14 % for Barisal. Looking at the overall findings mentioned above, it can be concluded that model's performance is satisfactory enough to estimate the future rice production in Bangladesh.

3.4 Yields under different planting times

In a changed climate, response of water-limited yields of the studied rice cultivar to transplanting time shifting was assessed by selecting four different planting dates and compared with the present. A case study was carried out for January 8, 18, and 28 and February 7 of all individual years during the periods 2000–2008, 2046–2065, and 2081–2100. Selected districts were Rangpur, Faridpur, and Barisal. Compared to the period 2000–2008, a significant reduction in water limited yields of the studied rice cultivar appeared, due to the projected climate change in future in all three locations. For the districts, the model simulated the average water-limited yields as 3.80 tons ha^{-1} during 2000–2008, with the planting date January 18 (Table 3). However, about 2.51 and 2.58 tons ha^{-1} of yield over the periods 2046–2065 and 2081–2100, respectively, were estimated for the same districts and same planting date. In comparison with the production locations, somewhat higher reductions were suggested for the central district of Faridpur, 40 and 46 %, respectively, for the period of 2046–2065 and 2081–2100 with the fixed planting date January 18.

Combined for both the future time spells, average yield reductions for the districts were about 36, 33, 28, and 24 %, respectively, for planting dates of January 8, 18, and 28 and February 7. As a whole, the predictions indicated a significant reduction in rice yield for early planting, especially before January 28. Although in the future, late planting would be beneficial; however, a significant reduction in rice production might appear. Late planting in winter usually receives a higher rainfall during the vegetative growth, which results to some beneficial effects. However, increased temperature also affects the rice growth and the total production is hampered. Thus, it can be summarized that climate change would cause significant variation in winter rice yield responding to varying transplanting time.

For the years 2050 and 2070, Basak et al. (2010) showed a 20 and 30 % average yield reduction, respectively, for two different winter rice varieties in Bangladesh. Also, Karim et al. (1996) showed a 0 to 6 % winter rice decline for the Canadian Centre for Climate Modelling scenario, while for Geophysical Fluid Dynamics Laboratory, the value was 4 to 11 %. These studies had the similar tendency of yield decline to the current one, although quantitative differences were observed. Mathauda et al. (2000) predicted an 8.4 % rice yield reduction for a 2°C temperature rise by the middle

Table 3 Predicted water-limited yields (in tons per hectare) and yield changes (in percent) for the rice cultivar over 2046–2065, 2081–2100, and 2000–2008 at three selected districts in Bangladesh

Districts	January 8				January 18				January 28				February 7			
	2046–2065	2081–2100	2000–2008	% yield change in the future	2046–2065	2081–2100	2000–2008	% yield change in the future	2046–2065	2081–2100	2000–2008	% yield change in the future	2046–2065	2081–2100	2000–2008	% yield change in the future
Rangpur	2.49	2.80	4.08	−35.17	2.70	3.02	4.10	−30.24	3.17	3.07	4.19	−25.71	3.13	3.26	4.12	−22.45
Faridpur	2.29	2.03	3.84	−43.75	2.31	2.06	3.85	−43.37	2.47	2.24	3.78	−37.73	2.41	2.44	3.58	−32.31
Barisal	2.40	2.51	3.45	−28.69	2.52	2.66	3.44	−24.70	2.59	2.68	3.29	−19.91	2.63	2.77	3.22	−16.14
Average	2.39	2.45	3.79	−35.87	2.51	2.58	3.80	−32.77	2.74	2.67	3.76	−27.78	2.72	2.82	3.64	−23.63

of the current century. In the future, growing duration of rice is expected to be shorter due to extremely warm conditions. As a consequence, yield reduction is expected. Higher temperatures associated with increased cloudiness would cause spikelet sterility that may also cause yield reduction. Accelerated respiration above 22°C would be the main reason for shortened grain-filling period and thereby declined net assimilation will produce less rice.

Projected climate with an average monthly temperature of 33°C will cause severe sterility and yield reduction is clear. Extremely high temperatures (greater than 32°C), projected for the periods 2081–2100, are really alarming, since these exceeds the optimum temperature limit of 25–30°C for the highest photosynthesis. Also, under the warm climatic scenarios, the reduced leaf area coupled with poor sink strength will reduce the number of effective tillers. In association with changed solar radiation, this might cause considerable yield reduction. With air temperature above normal and with the changed solar radiation, the duration of physiological maturity and the length of individual growth stage decreased steadily, which were the main reasons for low production.

3.5 Water demand

Following the alternate wetting and drying and submerged irrigation schemes, with January 18 plantation, water requirements of the studied rice cultivar are presented in Fig. 3. In comparison with the periods 2000–2008, higher water demand in the future is observed for both irrigation treatments. Only for a few examples, the differences are noted here from the current status and/or the plantation date of January 18 with the alternate wetting and drying irrigation scheme. More water would be needed by 14 % for 2046–2065 and 13 % for 2081–2100 for January 18 plantation. As the plantation dates delay, water requirement increases become more sensitive, i.e., the combined values for 2046–2065 and 2081–2100 were 16 and 20 % for the plantation dates of January 28 and February 7, respectively. In the future, changed rainfall pattern with a higher temperature will enhance the evapotranspiration by increasing the water demand for the late cropping. Following the most productive plantation date January 18, the central district Faridpur would be affected most. On the contrary, a smaller impact was found on the southern district of Barisal, having somewhat more rainfall in the coming days compared to the present situation.

Warmer climate associated with increased solar radiation leads to high evapotranspiration, which might be the main reason for higher water demand in the coming years. Bangladesh passed through several major droughts having disastrous crop failure in recent years (for example, 1979, 1982, 1990, 1994, and 1995), which might be more common in future. In Bangladesh, Bangladesh Agricultural Research Council (1990) estimated rice yield reduction as 10 to 70 %, depending on the severity of drought. These references support the significance of water demand analysis in the present study, altogether suggesting the necessity of adaptation measures to cope with projected climate change.

Karim et al. (1999) reported that, in Bangladesh, winter rice was benefited even by a little rainfall in early February. During winter, cropping season soil moisture was found to be lowest at all studied districts of Bangladesh compared to the monsoon and summer. Projection showing a significant decline in future winter rainfall in Bangladesh will make the situation worsen. Less rainfall accompanied by higher temperature might lead to drought and death rate of plants may increase in such a situation, reducing rice production.

According to Lal et al. (1998), a 20 % net decline in rice production occurred due to moderate water shortage in India. Also shown by Mahmood et al. (2004), in Bangladesh, high water stress during maturing, flowering, or in both periods resulted in wet season rice yield reductions of 37, 46, and 73 %, respectively, compared to lower stress with the transplant date of June 1. The effect of water

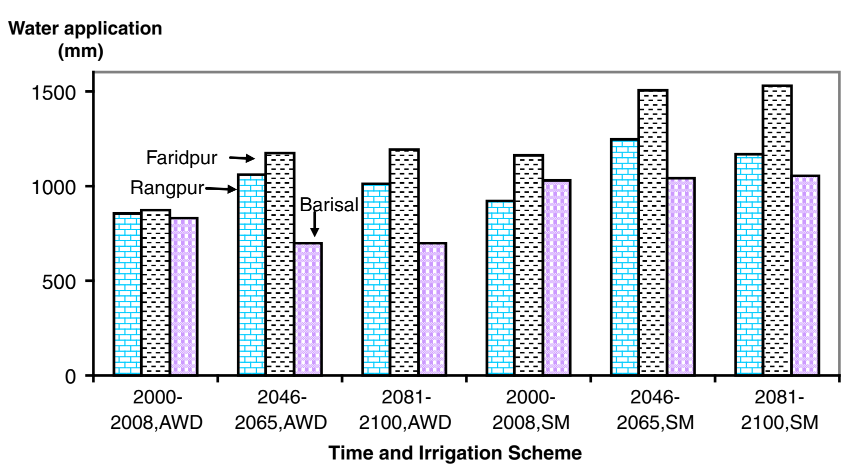

Fig. 3 Predicted water demand for the studied rice cultivar at Rangpur, Faridpur, and Barisal. *AWD* alternate wetting and drying irrigation (175 mm water application after 6 days of water disappearance), *SM* submerged irrigation (10 mm water logged during the growing season)

stress on winter rice would be similar to that of wet season, even more crucial in some years in the future. Since most part of Bangladesh occupies dry land and falls in an arid zone during winter, even a little winter rainfall decrease in the future would have a strong negative influence on rice production. The situation would be more critical in the future for early planted rice having the lowest rainfall projection. Earlier mentioned findings supported the current result by showing the crucial scenario of rice production in future in Bangladesh.

4 Conclusion

To examine the consequences of global warming on a winter rice cultivar in Bangladesh, a simulation study was conducted using the rice growth simulation model ORYZA2000. Nine major rice-growing districts were identified first to look at the current trend during 2000–2008. Then, predictions were made for three locations in which climate change data were available. Recommended datasets of climate, soil, and rice were gathered from relevant agencies. The model's performance was found to be satisfactory and acceptable to extrapolate the measured data under interannual variability toward the future scenario.

Among all the planting dates, February 7 is recommended as the best planting time for future causing less yield damage. However, still relatively to the present time practice of January 18, the yields of the studied rice cultivar will be hampered by 33 %, combining the periods 2046–2065 and 2081–2100. More water would be demanded by 14 %, for the future time spells with 18 January plantation and alternate wetting and drying practice. Because of the water scarcity, Faridpur will be affected more with the current planting practice. Other consequences of climate change would be the shorter growing season for the future days.

By acknowledging the significant uncertainties of climatic projection, it can be concluded that even a little increase in winter temperatures together with less rainfall would cause severe grain sterility in rice. Parameters on various rice growth and development stages need to be measured very carefully, while comparison is suggested with the results of controlled experiments. The use of a drought-resistant rice variety and conservation of water are important for future days. In the districts where early plantation is currently practiced, planting date shifting would be a simple but powerful strategy to have some positive consequences on drastic effects of climate change. Reliable prediction of crop production in the future will depend on a clearer understanding of the relationship between rice and climate. ORYZA2000 could be a very useful tool in assessing possible impacts of climate change on other popular rice varieties in Bangladesh. However, the use of calibrated data from high-resolution climate model can help for the advancement of prediction.

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