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Impacts of air temperature variations on the boro rice phenology in Bangladesh: implications for irrigation requirements

Rezaul Mahmood

Department of Geography, College of Geosciences, The University of Oklahoma, Norman, OK 73019, USA

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Abstract

Air temperature significantly affects crop phenology. Numerous experiments have shown that prevailing air temperature determines the length of crop growth stages. Irrigation field requirements depend on the length of the crop growth stages. In the present study, a physically based parametric model, YIELD, has been applied to estimate the impacts of fluctuating air temperature (due to inter-annual climatic variability and global warming) on evapotranspiration water requirements and the length of growth stages of the irrigated boro rice in Bangladesh. The YIELD model is crop specific and crop-growth-stage specific which is a compromise between area-specific regression models and complex crop growth simulation models. The model was tuned to Bangladesh's environment to represent appropriate agro-ecological conditions including soil type, depth of ground water, field size, wind regime, and percolation losses. YIELD has been validated for the length of the growth stages, length of growing season, final yield, and evapotranspiration. A baseline estimate for the boro rice phenology has been established by running the model for 12 meteorological stations located in the major rice growing regions.

Based on the analysis of the past variations of air temperature and general circulation model (GCM) predictions, ten scenarios have been created to estimate the effects of these variations on the boro rice growth stages. These applications find that the planting date plays an important role in the boro rice phenology. This effect is most noticeable during initial growth stages. This study has found a non-linear relationship between decreasing air temperature and the length of the initial growth stage and a predominantly linear relationship with other growth stages. Model applications show that an increase in air temperature will provide longer and more stable thermal conditions for boro rice maturing stage. A 5% increase and a 4% decrease in seasonal total evapotranspiration will occur under each 1° cooler and warmer air temperature conditions, respectively. A rise in evapotranspiration will cause higher demands for irrigation water. Such conditions will put pressure on the current irrigation infra-structural facilities in Bangladesh and result in reduction of boro yields. Furthermore, variations in the percent of time required for the completion of different growth stages under various air temperature conditions will demand a reorganization of irrigation schedules.

Keywords: Air temperature variations; Boro rice phenology; Irrigation requirements

1. Introduction

Numerous studies have shown that temperature plays an important role in rice plant physiology and growth (Munakata, 1976; Nishiyama, 1976; De Datta, 1981; Yoshida, 1981; Haque, 1986; Oldeman et al., 1987). Air temperature variations influence germination (Yoshida, 1981, Yoshida, 1983), seedling growth (Yoshida, 1981), and vegetative and reproductive growth (Munakata, 1976; Nishiyama, 1976). Haque (1987), Oldeman et al. (1987), and Yoshida (1983) noted that higher and lower air temperatures reduce

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and extend lengths of rice plant growth stages, respectively, and influence the length of the total growing season. Thus, inter- and intra-annual temperature fluctuations can affect the rice plant's physiology and related growth parameters. In addition to these temperature fluctuations, $2 \times CO_2$ induced global temperature increases are a major threat to world-wide agricultural practices (Parry et al., 1985; Parry and Carter, 1990; Parry, 1992; Rosenzweig and Hillel, 1993; Rosenzweig and Parry, 1994). In a previous paper, Mahmood and Hayes (1995) presented the possible impacts of abnormal thermal and solar climate on the winter season boro rice yield, the length of the boro rice growing season, and several other growth related parameters. This study assesses the impacts of cooler or warmer temperature on the length of the individual growth stages of boro rice in Bangladesh. Additionally, the impacts of

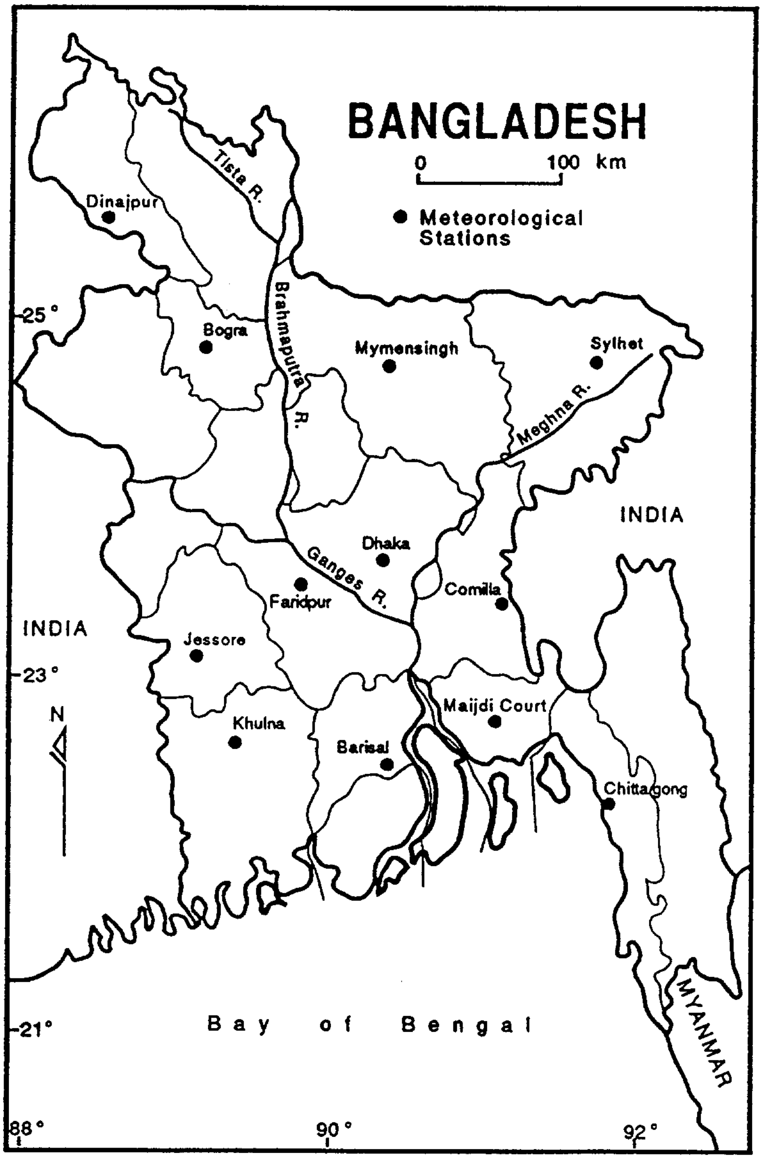

Fig. 1. Location of meteorological stations in Bangladesh.

these abnormal thermal conditions on the irrigation requirements have been investigated. A crop growth simulation model, YIELD (Hayes et al., 1982a, Hayes et al., 1982b) has been applied to ten synthetically fluctuated air temperature scenarios to assess impacts of abnormal thermal conditions on the length of growth stages and irrigation requirements. The YIELD model is able to simulate and predict seasonal crop yield and growth parameters for 11 crops including rice. A set of 12 meteorological stations, well distributed over the major rice growing regions in Bangladesh, have been selected and used in this study (Fig. 1). Furthermore, these stations are consolidated into three groups based on their latitudinal locations.

2. The rice growing seasons and irrigation facilities in Bangladesh

Favorable hydroclimatic conditions allow Bangladeshi farmers to grow rice year round. The three major rice crops are boro, aus, and aman. The growing season for boro, aus, and aman starts and ends during the months of December and May, March and August, and June and November, respectively. These growing seasons nearly synchronize with the three climatic seasons namely, winter (November through February), the hot summer (March through May), and the monsoon (June through October). Table 1 presents climatic features of the three rice growing seasons.

Bangladesh Rice Research Institute (BRRI) reported that 85% of the boro rice varieties cultivated in Bangladesh are irrigated modern varieties (BRRI, 1991). Since boro rice grows during the dry winter and the hot summer season its water requirements are fulfilled by irrigation. Aus rice requires supplemental irrigation during the first part of its growing season while aman is a rain-fed rice that grows during monsoon months.

Due to improvements in irrigation facilities over the last few decades, the share of boro rice production in Bangladesh has increased from 5% of the total production in the early 1960s to 20% in the mid-1970s and 26% during the mid-1980s (BRRI, 1988). During 1976–77 cropping season, 1 216 000 ha of agricultural lands were provided with irrigation water by using both modern and traditional methods. In 1980–81 1 639 000 ha of agricultural lands were supplied with irrigation water while in 1984–85 the area irrigated increased to 2 074 000 ha (Choudhuri, 1988). Moreover, improvements in irrigation facilities have reduced the boro rice's dependence on rain and largely eliminated the effects of deficient rainfall. These conditions have encouraged local authorities to emphasize an increase in boro rice cultivation and have further influenced the expansion of irrigation facilities.

3. The YIELD model

The YIELD model evolved from a crop water balance model called WATER developed by Burt et al. (1980), Burt et al. (1981). It has been validated for several major agricultural crops including rice, grain corn, wheat, barley, potato, and alfalfa (Burt et al., 1980, Burt et al., 1981; Mearns, 1982; Hayes et al., 1982a, Hayes et al., 1982b). YIELD model has been successfully applied to several regional studies including Australia (Mearns, 1982), China (Terjung et al., 1983, Terjung et al., 1984a, Terjung et al., 1984b, Terjung et al., 1984c, Terjung et al., 1984d,

Table 1
Important features of climate of Bangladesh during the three rice growing seasons

Rice cropping seasons	T_{max} (°C)	T_{min} (°C)	Q (MJ m^{-2} day^{-1})	Precipitation (mm)
Aus (Mar–Aug)	34–31	16–26	14–23	1200–3100
Aman (June–Nov)	34–28	26–16	14–19	1250–3000
Boro (Dec–May)	24–34	10–26	14–23	250–550

T_{max}, mean maximum air temperature; T_{min}, mean minimum air temperature; Q, solar radiation.
Ascending and descending values for T_{max}, T_{min}, and Q represent respective increase and decrease as rice growing season progresses. Precipitation shows seasonal total with regional variation.

Terjung et al., 1984e, Terjung et al., 1984f, Terjung et al., 1985, Terjung et al., 1989; Todhunter et al., 1989), the North American Great Plains (Terjung et al., 1984g; Liverman et al., 1986), California (Hayes, 1986), and Bangladesh (Mahmood, 1993; Mahmood and Hayes, 1995).

The YIELD model's evapotranspiration calculation is based upon methods developed by Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979). They have used the Penman (1948) equation to calculate evapotranspiration (ET). Penman's equation combines energy balance and aerodynamic functions to calculate evapotranspiration. Doorenbos and Pruitt (1977) successfully modified this equation for

Table 2
Summary of ET related equations used in the YIELD model

ET of reference crop (CROP1) (mm day^{-1})	
CROP1 = [(1. − WIHU) * RN + [WIHU * WIFU * (ES − EA)	(1)
RN = QAB − IAB	(2)
IAB = 0.01695 * FTEMP * FEA * FNN	(3)
FTEMP = SIGMA * (TMEAN + 273.16) * * 4	(4)
FEA = 0.34 − 0.044 * SQRT (EA)	(5)
FNN = 0.1 + 0.9 * (1. − N)	(6)
WIFU = 0.277 * (1. + *V* * 0.386)	(7)
ET, wind, radiation, and humidity adjustments (WIADJ)	
CROP2 = CROP1 * WIADJ	(8)
ET crop coefficient adjustments (COEFF)	
CROP3 = CROP2 * COEFF	(9)
ET clothsline and oasis adjustments (OASIS)	
CROP4 = CROP3 * OASIS	(10)
ET adjustments for soil water budget, precipitation	
CROP5 = CROP4 * WATER	(11)

WIHU = weighting factor for wind and humidity effects
WIFU = wind function
QAB = absorbed shortwave radiation, expressed as equivalent water evaporated (mm). The water equivalent of the latent heat of vaporization (*L*) depends very slightly on temperature. At 20°C, *L* equals 585 cal gm^{-1}. Changing the temperature plus or minus 10°C results in changes in *L* of less than 1%
IAB = net longwave radiation (mm) = SIGMA * (TMEAN + 273.16 * * 4) * FEA * FNN * 0.01695
SIGMA = Stefan–Boltzmann constant
FEA = humidity function for longwave radiation calculation
FNN = cloud function
QAB − IAB = net radiation
EA = actual vapor pressure (mb)
ES = saturation vapor pressure (mb)
ES − EA = vapor pressure gradient (mb)
FTEMP = longwave radiation produced by temperature (W m^{-2})
TMEAN = mean daily air temperature (°C)
V = wind velocity (mm s^{-1})
N = cloud amount (fraction)
CROP1 = reference crop ET (mm day^{-1})
CROP2 = adjusted reference crop ET (mm day^{-1})
CROP3 = maximum crop ET (ETp) (mm day^{-1})
CROP4 = maximum crop ET adjusted for clothsline and oasis effects (mm day^{-1})
CROP5 = actual crop ET (ETa) accounting for soil moisture conditions (mm day^{-1})

Source: Hayes (1986).

reference crops (which is an extended surface of 8 to 15 cm tall, green grass cover of uniform height, actively growing, completely shading the ground and not short of water). The modified equation included the effects of crop type, crop-growth-stage, selected site factors, influence of unusual climatic conditions, ET adjusting crop coefficients ET for specific crops and specific crop growth stages, and soil moisture budget conditions. The submodels CROP1, 2, 3, 4, and 5 constitute the calculation procedure for ET of the reference crop and actual crop (Table 2). The model calculates each variable for a set time step. In this study time step is 5 days. ET is the sum of radiative and moisture terms, involving net radiation and atmospheric vapor pressure deficit, respectively, in CROP1 (Doorenbos and Pruitt, 1977; Burt et al., 1980). CROP2 adjusts CROP1 for wind regimes, radiation amounts, and mean daily maximum relative humidity. CROP3 is the adjustment for CROP2 by crop-specific, growth-stage-specific coefficients which consider varying effects of crop growth stages on plant water use. CROP4 adjusts CROP3 for 'clothesline' and 'oasis' effects. Optimal water conditions have been assumed up to CROP4. CROP5 deals with an array of possible water stress situations of a specific crop and specific growth stages. For each crop and season, a soil water budget is calculated. In the YIELD model, soil water budgets are a function of a number of variables that includes growth-stage-specific ET, soil water storage, effective precipitation, groundwater contributions, variable root depths, and percolation losses. As this study assumes optimum supply of water, CROP5 is equal to CROP4. Further description of the YIELD model can be found in Burt et al. (1980) and Hayes et al. (1982b).

4. Input data and validation of the YIELD model for Bangladesh application

Long-term (1950–80) monthly average climate data of the 12 meteorological stations in Bangladesh have been used as model input in this study (Fig. 1). Mean monthly maximum and minimum air temperatures, mean monthly daily solar radiation, mean monthly wind speed, and precipitation data were obtained from the Food and Agricultural Organization of the United Nations (FAO, 1987). Mean monthly cloud cover and maximum and minimum relative humidity data were computed from the Bangladesh Meteorological Department's (BMD's) daily data (1975–1990). Data for monthly precipitation days of Sylhet, Bogra, Dhaka, Jessore, and Chittagong were obtained from Rudolff (1981) while that of the other stations were calculated from the BMD's daily data. The rice agronomy input data required for the model run is presented in Table 3.

4.1. Validation of the phenology submodel

The YIELD model adopts a phenology submodel partially developed from Doorenbos and Pruitt (1977). Burt et al. (1980) presented a detailed description of this procedure. The submodel is based upon the concept of cumulative degree days above a crop-specific threshold temperature which is a function of latitude. In other words, the accumulation of a certain amount of degree days of heat marks the end of a growth stage. In this study, a base temperature of 15°C (BRRI, 1991) has been used for these calculations (Table 3). The YIELD model has been applied to 1987 and 1988 data at BRRI's experiment

Table 3
Agronomic data inputs for calibration of the YIELD model

Model parameter	Value assigned	Source
Slope of the field	Flat	Mahmood (1993)
Soil type	Loamy	Mahmood (1993)
Root depth	Initial: 0.15 m; maximum: 0.50 m	Yoshida (1981)
Percolation loss rate	4 mm day^{-1}	BRRI (1991)
Harvest index	0.49	Biswas et al. (1989)
Base temperature	15°C	BRRI (1991)
Transplanting date	January 1	Mahmood (1993)
Day/night wind ratio	2:1	Mahmood (1993)

Table 4
Phenology submodel validation for Dhaka, Bangladesh

Growth stages (in days)	Doorenbos and Pruitt (1977)	Doorenbos and Kassam (1979)	Model run for 1987	Model run for 1988
Initial stage (1)	20	10	10	10
Vegetative stage (2)	35	40–60	60	60
Flowering/heading stage (3)	40	10–15	40	35
Maturing stage (4)	30	35–55	20	25

Table 5
Accumulated heat (°C) at the end of the growth Stages 1, 2, 3, and 4

Stations	Initial stage (1)	Vegetative stage (2)	Flowering/heading stage (3)	Maturing stage (4)
Northern region				
Sylhet	80.00	528.00	1051.00	1290.00
Bogra	80.00	528.00	1052.00	1291.00
Mymensingh	80.00	530.00	1055.00	1294.00
Dinajpur	80.00	515.00	1032.00	1273.00
Central region				
Dhaka	79.00	540.00	1071.00	1311.00
Faridpur	78.00	544.00	1078.00	1318.00
Comilla	78.00	546.00	1082.00	1323.00
Jessore	78.00	549.00	1087.00	1328.00
Southern region (with pronounced coastal influence)				
Chittagong	76.00	571.00	1126.00	1369.00
Khulna	78.00	554.00	1096.00	1337.00
Barisal	77.00	554.00	1096.00	1338.00
Maijdi Court	78.00	553.00	1094.00	1335.00

Table 6
Length of the individual growth stages (in days) for boro rice under normal climate

Stations	Initial stage (1)	Vegetative stage (2)	Flowering/heading stage (3)	Maturing stage (4)
Northern region				
Sylhet	20	65	45	25
Bogra	25	60	40	20
Mymensingh	20	60	45	20
Dinajpur	25	60	40	20
Central region				
Dhaka	15	65	40	20
Faridpur	20	65	40	20
Comilla	15	60	45	20
Jessore	15	60	40	20
Southern region (with pronounced coastal influence)				
Chittagong	15	65	45	25
Khulna	10	60	40	20
Barisal	15	60	40	20
Maijdi Court	10	65	40	25

station at Gazipur, Dhaka to evaluate its performance. The model-estimated number of days required to accumulate the heat to complete each growth stage have been compared to the rice phenology proposed by Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) and validated (Table 4). The differences between the Doorenbos and Pruitt (1977) and Doorenbos and Kassam (1979) proposed lengths of various growth stages and the YIELD model calculated length of growth stages result from the nature of local climate and the cultivar. Tables 5 and 6 present YIELD model-estimated cumulative degree days for each growth stage, and the length of each of the growth stage, respectively, for each station under 'normal' climatic conditions.

4.2. Validation of the ET submodel

Due to lack of published lysimeter and other consumptive use data it was very difficult to validate rice ET for Bangladesh. However, this study finds that BRRI recorded a total 741 mm ET for the 114 day long boro rice growing season during an experiment at the Dhaka station in 1982 (Fig. 2(a)) (BRRI, 1985). The YIELD model estimated 710 mm total growing season ET (140 day) at Dhaka, under normal climate conditions (Fig. 2(b)). The higher seasonal total ET in 1982 was most probably a result of higher mean maximum daily air temperatures during the boro rice growing season (BRRI, 1985). The shorter growing season indicates toward the higher mean maximum growing season air temperature in 1982. Additionally, the higher seasonal total ET in 1982 and the relatively shorter growing season results in higher ET rates (6 mm day^{-1}) compared with the model-predicted value (5 mm day^{-1}) under standard climatic conditions. Thus, it appears that model estimation of ET is satisfactory. Mahmood (1993) and Mahmood and Hayes (1995) provided a detailed description of tuning and validation of the model.

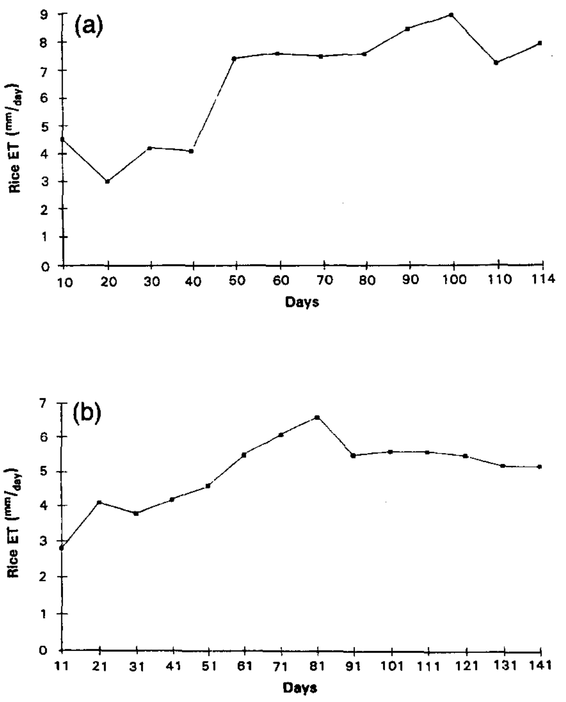

Fig. 2. (a) Daily ET measured at Dhaka in 1982. (b) The model estimated ET for Dhaka.

5. Thermal climate variability in Bangladesh

Mahmood and Hayes (1995) conducted a survey of monthly mean maximum and minimum and daily maximum and minimum air temperature for the boro rice growing season (January through May) for centrally located Dhaka from 1975 through 1990. It shows that the monthly mean maximum air temperatures deviate by up to 4°C and daily maximum temperatures deviate by up to 7°C from the long term monthly mean. It was found that monthly mean minimum and daily minimum temperatures fluctuated up to 2°C and up to 6°C, respectively, from the normal.

In recent years, advanced general circulation models (GCMs) have been applied to estimate the effects and extent of global warming over various regions of the world under $2 \times CO_2$ conditions. The Canadian Climate Center (CCC), the Geophysical Fluid Dynamics Laboratory (GFDL), and the United Kingdom Meteorological Office (UKMO) GCMs estimate a 2 to 4, 4 to 6, and 2 to 4°C increase of the winter season air temperature in Bangladesh, respectively (Mitchell et al., 1990). These models also suggest that precipitation would decrease by 1 to 2 mm day^{-1} during the winter season. Zhao and Kellogg (1988) performed a comparative study on the performance of five GCMs, namely, the GFDL, the

UKMO, the National Center for Atmospheric Research (NCAR), the Oregon State University (OSU), and the Goddard Institute for Space Studies (GISS), regarding the potential sensitivity of soil moisture to $2 \times CO_2$ conditions in the Asian monsoon region. All five GCMs predicted a decrease in soil moisture during the winter season in Bangladesh.

It is important to note that there are significant amount of uncertainties involved in these model predictions. The causes of these uncertainties are inherent in the structure of the model, model assumptions, and model physics. Ghan (1992) noted that size of the GCM grid cell is too large to capture many relatively smaller scale processes correctly. Increasing inaccuracy associated with the GCMs treatment of smaller scale advection and mixing are contributing in the uncertainty of the model predictions (Ghan, 1992). Furthermore, Dickinson (1989) suggested that the GCMs physics have been limited by our current insufficient knowledge of the various planetary processes. As a result, in many cases these processes and the related assumptions are unrealistic and oversimplified. Some of these poorly treated processes include transient adjustment controlled by ocean heat uptake, changes in the cloud cover and their radiative effect, changes in cloud optical properties, changes in atmospheric stability and moisture distribution, changes in sea-ice cover and their radiative effect, and surface hydrological responses.

Despite these uncertainties of the GCM predictions, the importance of their prognostications still contain significant value for the impact studies (Ghan, 1992). As such, based on the past records of variations in thermal climate of Bangladesh and the GCM predictions, ten scenarios have been created by deviating the mean air temperature (T_{air}) up to ± 5°C

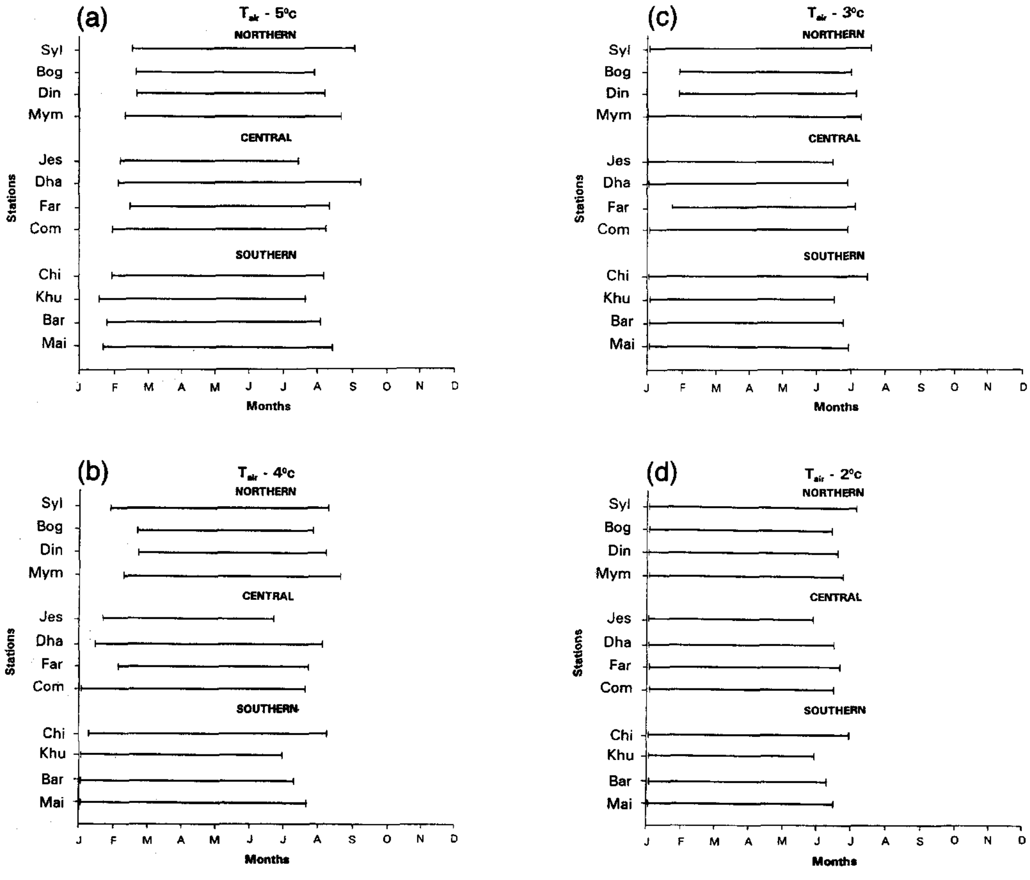

Fig. 3. The length of growing seasons over the northern, central, and southern region of Bangladesh under below normal thermal conditions.

with a 1°C interval. These scenarios have been applied to all 12 meteorological stations in Bangladesh to estimate the impacts of the variations in regional thermal climatic conditions on boro rice growing season and irrigation requirements.

6. Results and discussions

6.1. Effect of abnormal air temperature on the length of growing season

Fig. 3(a)–(d) presents transplanting and harvesting dates under reduced temperatures (below normal). Under the mean $T_{air} - 5$, -4, and -3°C scenarios, transplanting dates have been pushed from the originally specified date of January 1 to later dates to avoid possible frost. This study finds that under mean $T_{air} - 5$ and -4°C conditions, cooler northerly areas (e.g. Dinajpur, Bogra, and Sylhet) experience up to 7 weeks of late transplanting as compared with the Chittagong region which experiences up to 4 weeks of late transplanting due to relatively moderate coastal climate. Centrally located Dhaka has a transplanting date that lies between those of the northern and southern regions. Table 7 presents the model predicted length of boro rice growing seasons for the 12 meteorological stations under cooler thermal conditions. It is evident that in most cases, the length of the growing season increases with decreasing air temperature as there is a longer time requirements for the accumulation of heat to complete physiological cycles. Few exceptions to this trend occur due to the changes in transplanting date as a result of cooler thermal conditions. For example, in the case of Dinajpur the length of growing season decreases with increasing air temperature until $T_{air} -$ 3°C condition. Under $T_{air} - 2$°C condition, the length of boro rice growing season increases and equals the $T_{air} - 5$°C scenario. Due to the relatively less cool thermal climate, the model forces the transplanting date back to January 1 in Dinajpur. Although the transplanting date is back to the normal date, the growing season temperature is still cooler than normal conditions. This forces the rice plants to grow under cooler conditions for a longer period of time. As noted previously, this condition requires longer time period to accomplish plant physiological processes in Dinajpur, which results in longer growing season under $T_{air} - 2$°C scenario compared with T_{air} $- 4$ and -3°C scenarios. Under $T_{air} - 4$ and -3°C scenarios transplanting dates, are relatively closer to the warm season which causes a faster accumulation heat during the vegetative and flowering/heading

Table 7
Length of the boro rice growing season (number of days to reach maturity) in Bangladesh under standard, reduced, and increased mean T_{air} scenarios

Station	Normal climate	−5°C	−4°C	−3°C	−2°C	−1°C
Northern region						
Sylhet	155	200	190	200	185	170
Bogra	145	160	155	150	165	155
Mymensingh	145	190	180	190	175	160
Dinajpur	145	170	165	155	170	160
Central region						
Dhaka	140	185	190	180	165	150
Faridpur	145	180	170	165	170	155
Comilla	140	190	200	180	165	150
Jessore	135	160	155	165	150	140
Southern region (with pronounced coastal influence)						
Chittagong	150	220	210	195	180	165
Khulna	130	180	180	165	150	140
Barisal	135	190	190	175	160	145
Majdi Court	140	205	200	180	165	150

stages and an overall shorter growing season in Dinajur. Furthermore, warmer (above normal) air temperatures have resulted in a shorter than normal growing season for all the 12 stations due to faster accumulation of growing season heat. The following section of this paper will expand on the effects and impacts that cooler conditions have on individual growth stages and total growing season.

6.2. Effects of temperature variation on the length of boro rice growth stages

Table 8 presents the lengths of initial crop growth stage under below normal air temperature scenarios. The results presented in this table show that the lengths of the initial growth stage are shorter under mean $T_{air} - 5°C$ condition as compared with the mean $T_{air} - 4$, -3, -2, and $-1°C$ scenarios. It has already been recorded that due to cooler than normal air temperature the YIELD model pushed transplanting dates 2 to 7 weeks forward under $T_{air} - 5°C$ scenario (Fig. 3(a)). It has also been shown that this accelerates boro rice plant's entrance to the hot summer season within a short period of time. Furthermore, cooler than normal air temperatures also lead to a faster accumulation of heat and a quicker completion of the initial growth stage. Under $-4°C$ scenario, for all of the rice growing regions, the model moves the transplanting dates close to January 1 due to relatively less cool air temperatures. The $T_{air} - 4°C$ forces rice plants to grow under cooler conditions after transplanting during its initial growth stage. However, such thermal conditions require longer period of time to accumulate heat to complete the growth stage. In other words, $T_{air} - 4°C$ scenario produces a longer initial growth stage than the $T_{air} - 5°C$ scenario. The length of the initial growth stage also increases over the most of the rice growing regions under the mean $T_{air} - 3°C$ scenario. In the case of Khulna, Barisal, and Maijdi Court, the length of the initial growth stage starts decreasing from $T_{air} - 3°C$ scenario. This probably occurs because of pronounced coastal climatic effects. The length of the initial growth stage continues to increase in Bogra and Dinajpur up to mean $T_{air} - 2°C$ scenario due to cooler air temperatures (Table 8). Under the mean $T_{air} - 2°C$ scenario transplanting dates at Bogra and Dinajpur are set to January 1 due to comparatively higher air temperatures. Although temperatures increase in Bogra and Dinajpur, in general they are still low compared with other regions. The combination of cooler northerly locations and lower air temperatures resulted in longer initial growth stage in Bogra and Dinajpur compared with others under the mean $T_{air} - 2°C$ conditions. In the mean time, lengths of vegetative, flowering/heading, and matur-

Table 8
Length of initial growth stage (in days) under below normal thermal conditions

Station	Standard climate	−5°C	−4°C	−3°C	−2°C	−1°C
Northern region						
Sylhet	20	25	35	50	35	25
Bogra	25	20	25	25	50	35
Mymensingh	20	25	30	50	35	25
Dinajpur	25	20	25	30	50	35
Central region						
Dhaka	15	25	35	40	30	20
Faridpur	20	20	25	30	40	30
Comilla	15	30	50	40	30	20
Jessore	15	25	30	40	30	20
Southern region (with pronounced coastal influence)						
Chittagong	15	30	40	40	25	20
Khulna	10	35	40	30	20	15
Barisal	15	30	45	35	25	20
Maijdi Court	10	35	45	35	25	15

ing stages continue to decrease with increasing air temperatures. Hence, the initial growth stage does not show a linear relationship with decreasing air temperature. As already shown, the YIELD model calculated transplanting dates play an important role in this non-linear relationship.

Under above normal air temperature conditions, the length of the boro rice growing season and the lengths of individual growth stages (except for the maturing stage) decrease steadily. The model estimates minor changes in the length of the maturing stage under increased air temperature conditions (Table 9). Model calculated shortening of the length of the boro rice growing season moves the maturing stage backward up to 6 weeks. A relatively stable length of the maturing stage under these increasing temperature scenarios indicates that thermal conditions for this 6 weeks period are favorable for boro rice maturing. The availability of such a long favorable thermal environment is encouraging news for Bangladeshi farmers.

6.3. *Effect of synthetically fluctuated air temperature on evapotranspiration*

Fig. 4 shows the boro rice growing season total evapotranspiration under synthetically fluctuated thermal conditions. Seasonal total evapotranspiration has increased under reduced air temperature due to a longer growing season (Fig. 5). Opposite results

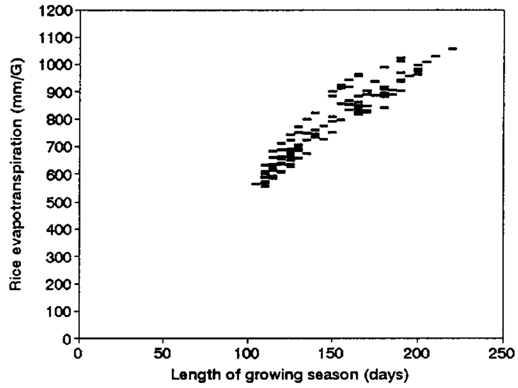

Fig. 4. Length of growing season vs. boro rice ET in Bangladesh.

occur under increased air temperature conditions. The model calculates that the average seasonal total evapotranspiration increases 37 mm or 5% with each 1°C decrease of air temperature. Furthermore, seasonal total evapotranspiration decreases with increasing air temperature because of a shorter growing season. On average, seasonal evapotranspiration decreases 32 mm or 4% with each 1°C air temperature increase.

6.4. *Impacts of variable length of growth stages on water requirements and irrigation facilities*

Table 10 presents additional water requirements for boro rice growing areas under cooler climates. It

Table 9
Length of maturing stage (in days) under above normal thermal conditions

Station	Standard climate	+1°C	+2°C	+3°C	+4°C	+5°C
Northern region						
Sylhet	25	25	25	20	25	20
Bogra	20	20	20	20	20	20
Mymensingh	20	20	20	20	20	20
Dinajpur	20	25	20	20	25	25
Central region						
Dhaka	20	20	20	25	25	20
Faridpur	20	20	20	25	25	25
Comilla	20	20	25	25	25	25
Jessore	20	25	25	25	25	20
Southern region (with pronounced coastal influence)						
Chittagong	25	20	20	25	25	25
Khulna	20	20	20	20	20	20
Barisal	20	25	20	20	20	20
Maijdi Court	25	20	25	20	20	25

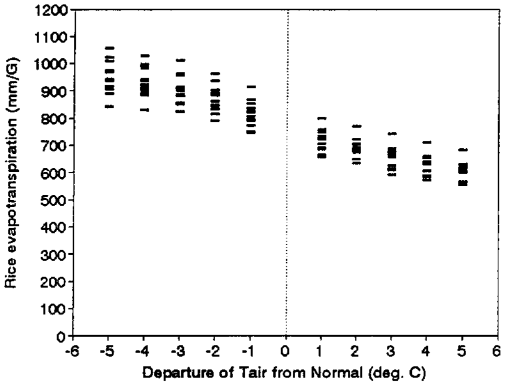

Fig. 5. Boro rice ET in Bangladesh under abnormal thermal conditions.

is evident that irrigation water requirements will increase due to the longer growing season which results from the below normal growing season air temperatures. In other words, a longer growing season means longer individual growth stages in most cases. This also means higher irrigation water requirements for each growth stage. The model estimates that the demand of water will increase up to 25% under the $T_{air} - 5°C$ scenario requiring an additional 2.42×10^9 m^3 of water. Table 11 presents the average percent of time required to complete individual growth stages under five different thermal conditions (average total length of growing season is 100%). The YIELD model estimates that the percent of time required to complete growth Stage 1 will continue to increase through the mean $T_{air} - 5°C$, $-4°C$, and $-3°C$ conditions. The percent of time required to complete Stage 2 starts increasing from $T_{air} - 3°C$ scenario and continues up to $T_{air} - 1°C$ scenario. Moreover, the percent of time required to complete Stages 3 and 4 continue to decrease with increasing temperature. Doorenbos and Kassam (1979) noted that a sufficient supply of water is necessary to recover from transplanting. Thus, a longer initial stage requires that irrigation planners to reschedule irrigation. In addition, they found that evapotranspiration increases as vegetative growth (Stage 2) progresses. Evapotranspiration reaches its maximum shortly before the flowering to early yield formation stage (Doorenbos and Kassam, 1979). Fluctuations in the length of the Stage 2 also requires rearranging of irrigation schedule.

Rogers et al. (1989) noted that Bangladesh is using only 25% of its irrigation potential. Lack of irrigation pumps, insufficient maintenance facilities, and the high cost of energy are notable causes of failure to utilize available water resources. Increased

Table 10
Irrigation water requirements under cooler air temperature conditions

	Standard climate	−5°C	−4°C	−3°C	−2°C	−1°C
Average ET for Bangladesh (mm)	761	949	935	910	873	816
Percent (%) of increase in ET		25	23	19	15	7
Volume of additional water requirements for Bangladesh (m^3)		2.42×10^9	2.23×10^9	1.92×10^9	1.44×10^9	7.07×10^8

Area under boro rice cultivation = 1 285 830 ha (Choudhuri, 1988).

Table 11
Percent time required to complete individual growth stages under below normal air temperature

Deviation of temperature from the normal	Initial growth stage (%)	Vegetative stage (%)	Flowering/heading stage (%)	Maturing stage (%)
−5°C	14.00	35.00	32.00	19.00
−4°C	19.45	33.65	30.44	16.25
−3°C	21.20	35.00	28.09	15.71
−2°C	20.00	37.40	27.40	15.20
−1°C	15.00	42.00	28.00	15.00

Length of the total growing season is 100% time.

irrigation water requirements due to a longer growing season under cooler environments will only make the current situation worse by overloading existing facilities. It has been noted earlier that there is a very high possibility of drier than present winter soil moisture conditions in Bangladesh because of $2 \times CO_2$ induced global warming (Zhao and Kellogg, 1988; Mitchell et al., 1990). The drier conditions will increase the demand of water supply. Although it is noted that 85% of the area under boro rice cultivation receives water through irrigation, the supply of water is not optimum in many cases. Higher demands for water due to the drier and the cooler climate will increase the gap between demand and supply of water, and will reduce evapotranspiration. This, in turn, will reduce boro rice productivity (Mahmood, 1993; Mahmood and Hayes, 1995). The warmer conditions (as predicted by the GCMs) will result in shorter growing season and cause slight increase in daily evapotranspiration rate. Although daily evapotranspiration rate increases, the shorter growing season will result in the reduction of the end of the season total evapotranspiration.

7. Conclusions

The YIELD model has been applied to 12 major rice growing regions for ten air temperature variation scenarios. These scenarios represent cooler or warmer growing season air temperatures and possible global warming conditions. The present study estimates a non-linear relationship between decreasing air temperature and the length of the initial growth stage and a largely linear relationship with other growth stages. Under $T_{air} - 5$°C condition, the YIELD model pushes transplanting dates 2–7 weeks forward causing a relatively quick entrance of the boro rice plants into the summer season. This results in shorter initial growth stage under $T_{air} - 5$°C scenario compared with $T_{air} - 4$, -3, and -2°C scenarios. As air temperature increases from $T_{air} - 5$°C to $T_{air} - 3$°C conditions, the length of initial growth stages also increases. Increasing air temperatures push transplanting dates close to January 1 and force rice plants to grow under a cooler thermal climate. Such climate conditions require a longer time for boro rice to complete initial growth stage. This study finds that seasonal total evapotranspiration will increase up to 5% under each 1°C cooler than normal conditions. A rise in evapotranspiration will result in higher demands for irrigation water. These conditions will put tremendous pressure on the current irrigation facilities in Bangladesh and result in reduction of boro rice yields.

The model application shows that an increase in air temperature will provide longer and more stable thermal conditions for the boro rice maturing stage. A 4% decrease in seasonal total evapotranspiration will occur under each 1°C increased air temperature conditions. The warmer air temperature conditions will result in shorter growing season and reduce end of the season total evapotranspiration. Furthermore, the variations in the percent of time required for the completion of different growth stages under various air temperature conditions will require a reorganization of irrigation schedules.

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