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ORIGINAL PAPER

Egyptian cotton (*Gossypium barbadense*) flower and boll production as affected by climatic factors and soil moisture status

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Abstract The information on impact of climatic factors on cotton production is not generally available, or at least not available in the required form. Understanding this impact may help physiologists determine a possible control of the flowering mechanism in the cotton plant. Two field trials were conducted to investigate the relationships between climatic factors, soil moisture status, and flower and boll production of *Gossypium barbadense*. The climatic factors considered were daily maximum air temperature (°C), minimum air temperature (°C), maximum–minimum temperature (diurnal temperature range) (°C), sunshine duration (h day^{-1}), maximum relative humidity (%), minimum relative humidity (%), and wind speed (m s^{-1}). Minimum relative humidity and sunshine duration were the most significant climatic factors affecting flower and boll retention and production. Temperature appeared to be less important in the reproduction growth stage of cotton in Egypt than minimum relative humidity and sunshine duration. The soil moisture status showed low and insignificant correlation to flower and boll production. High minimum relative humidity, short period of sunshine duration, and low temperatures enhanced flower and boll formation.

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1 Introduction

Understanding climatic factors in addition to soil moisture status on cotton production may help physiologists determine possible control of flowering of the cotton plant.

Climate affects crop growth interactively, sometimes resulting in unexpected responses to prevailing conditions. The balance between vegetative and reproductive development can be influenced by soil fertility, soil moisture, cloudy weather, spacing and perhaps other factors such as temperature and relative humidity (Guinn 1982). Weather, soil, cultivars, and cultural practices affect crop growth interactively, sometimes resulting in plants responding in unexpected ways to their conditions (Hodges et al. 1993).

Water is a primary factor controlling plant growth. Luz et al. (1998) indicated that, in a field trial in Condado, Paraiba, Brazil, cotton cv. BR 1 was subjected to water stress at 1, 2, or 3 of the following stages: pre-flowering (PF), flowering/fruiting (FF), and maturity. Water stress at PF + FF reduced yield by 48% compared with the control. Irrigation only at FF resulted in yield 5% lower than in the control, and this treatment had the highest water use efficiency. Xiao et al. (2000) stated that, when water was applied at 0.85, 0.70, 0.55, or 0.40 ET (evapotranspiration) to cotton plants grown in pots, there was a close relationship between plant development and water supply. The fruit-bearing branches, square, and boll numbers and boll size were increased with increased water supply.

Barbour and Farquhar (2000) reported on greenhouse pot trials where cotton cv. CS50 plants were grown at 43% or 76% relative humidity (RH) and sprayed daily with abscisic acid (ABA) or distilled water. Plants grown at lower RH had higher transpiration rates, lower leaf temperatures, and lower stomatal conductance. Plant biomass was also reduced at the lower RH. Within each RH environment, increasing ABA concentration generally reduced stomatal conductance, evaporation rates, superficial leaf density and plant biomass, and increased leaf temperature and specific leaf area. Oosterhuis (1999) stated that, high day/night temperatures and water stress result in low boll weights and reduced cotton yields. Yuan et al. (2002) reported that, correlation analysis of meteorological data (1987–1995) showed that under the semiarid ecological conditions on the Loess Plateau, dryness is the main factor limiting the development of cotton production.

Temperature is also a primary factor controlling rates of plant growth and development. Burke et al. (1988) has defined the optimum temperature range for biochemical and metabolic activities of plants as the thermal kinetic window (TKW). Plant temperatures above or below the TKW result in stress that limits growth and yield. The TKW for cotton growth is 23.5°C to 32°C, with an optimum temperature of 28°C. Biomass production is directly related to the amount of time that foliage temperature is within the TKW. Reddy et al. (1990) found that cotton cv. ST825 plants grown at optimum temperature (30°C/20°C day/night temperature) partitioned nearly 43% of their total biomass to reproductive structures (bolls and squares) compared with 13–15% for plants grown at a lower temperature. At higher temperatures, biomass partitioned to reproductive parts was negligible. Reddy et al. (1995a) in growth chamber experiments found that Pima cotton cv. S-6 produced lower total biomass at 35.5°C than at 26.9°C, and no bolls were produced at the higher temperature of 40°C. Reddy et al. (1999) utilized naturally lit plant growth chambers to determine the influence of temperature and atmospheric [CO_2] on cotton (*Gossypium hirsutum* cv. DPL-51) boll and fiber growth parameters. Boll size and maturation periods decreased as temperature increased. Boll growth increased with temperature to 25°C and then declined at the highest temperature. The upper limit for cotton boll survival is 32°C.

General circulation models (GCMs) project increases of the earth's surface air temperatures and other climate changes in the middle or latter part of the 21st century will expose crops such as cotton (*Gossypium hirsutum* L.) to much different environments than what exist today (Reddy et al. 2002). To understand the implications of climate change on cotton production in the Mississippi Delta, 30 years (1964 to 1993) of cotton growth and yield at Stoneville, Mississippi, USA, were simulated using the cotton simulation model GOSSYM. The GCM projections showed a 4°C rise in average temperature and a decrease in precipitation during the crop-growing season. The rate of plant growth and development was higher in the future because of enhanced metabolic rates at higher temperatures combined with increased carbon availability. The effect of climate change on cotton production was more drastic in a hot/dry year. Since most of the days with average temperatures above 32°C will likely occur during the reproductive phase, irrigation will be needed to satisfy the high water demand, and this reduces boll abscission by lowering canopy temperature. Cultural practices such as earlier planting may be used to avoid the flowering of cotton in the high temperatures that occur during mid- to late summer (Reddy et al. 2002). Schrader et al. (2004) stated that high temperatures that plants are likely to experience inhibit photosynthesis. Reddy et al. (1992) found in a study of Upland cotton that the number of bolls produced, bolls retained, and percent retention were progressively reduced as the duration of 40°C canopy temperature increased. Three weeks exposure to 40°C for 2 or 12 h $days^{-1}$ resulted in 64 or 0% bolls retained on the plant, respectively. Zhou et al. (2000) indicated that light duration is the key meteorological factor influencing the wheat–cotton cropping pattern and position of the bolls, while temperature had an important function on upper (nodes 7 to 9) and top (node 10) bolls, especially for double cropping patterns with early maturing varieties.

The objective of this investigation was to study the effect of various climatic factors and soil moisture status during the development stage on flower and boll production in Egyptian cotton. This could result in formulating advanced predictions as to the effect of certain climatic conditions on production of Egyptian cotton. Minimizing the deleterious effects of the factors through utilizing proper cultural practices will lead to improved cotton yield.

2 Materials and methods

Two uniform field trials were conducted at the experimental farm of the Agricultural Research Center, Ministry of Agriculture, Giza, Egypt (30° N, 31°: 28′ E at an altitude 19 m), using the cotton cultivar Giza 75 (*Gossypium barbadense* L.) in two successive seasons (I and II). The soil texture was a clay loam, with an alluvial substratum (pH=8.07, 42.13% clay, 27.35% silt, 22.54% fine sand, 3.22% coarse sand, 2.94% calcium carbonate, and 1.70% organic matter).

In Egypt, there are no rain-fed areas for cultivating cotton. Water for the field trials was applied using surface irrigation. Total water consumption during each of two growing seasons supplied by surface irrigation was about 6,000 m^3 h^{-1}. The criteria used to determine amount of water applied to the crop depended on soil water status. Irrigation was applied when soil water content reached about 35% of field capacity (0–60 cm). In season I, the field was irrigated on 15 March (at planting), 8 April (first irrigation), 29 April, 17 May, 31 May, 14 June, 1 July, 16 July, and 12 August. In season II, the field was irrigated on 23 March (planting date), 20 April (first irrigation), 8 May, 22 May, 1 June, 18 June, 3 July, 20 July, 7 August, and 28 August. Techniques normally used for growing cotton in Egypt were followed. Each experimental plot contained 13 to 15 ridges to facilitate proper surface irrigation. Ridge width was 60 cm, and length was 4 m. Seeds were sown on 15 and 23 March in seasons I and II, respectively, in hills 20 cm apart on one side of the ridge. Seedlings were thinned to two plants per hill 6 weeks after planting, resulting in a plant density of about 166,000 plants ha^{-1}. Phosphorus fertilizer was applied at a rate of 54 kg P_2O_5 ha^{-1} as calcium super phosphate during land preparation. Potassium fertilizer was applied at a rate of 57 kg K_2O ha^{-1} as potassium sulfate before the first irrigation (as a concentrated band close to the seed ridge). Nitrogen fertilizer was applied at a rate of 144 kg N ha^{-1} as ammonium nitrate in two equal doses: the first applied after thinning just before the second irrigation, and the second applied before the third irrigation. Rates of phosphorus, potassium, and nitrogen fertilizer were the same in both seasons. These amounts were determined based on the use of soil tests.

After thinning, 261 and 358 plants were randomly selected (precaution of border effect was taken into consideration by discarding the cotton plants in the first and last two hills of each ridge) from nine and 11 inner ridges of the plot seasons I and II, respectively. Pest control management was carried out on an as-needed basis, according to local practices performed at the experimental station.

Flowers on all selected plants were tagged in order to count and record the number of open flowers and set bolls on a daily basis. The flowering season commenced on the date of the first flower appearance and continued until the end of flowering season (31 August). The period of September (30 days) until 20 October harvest date allowed a minimum of 50 days to develop mature bolls. In season I, the flowering period extended from 17 June to 31 August, whereas in season II, the flowering period was from 21 June to 31 August. Flowers produced after 31 August were not expected to form sound harvestable bolls and therefore were not taken into account. For statistical analysis, the following data of the dependent variables were collected: number of tagged flowers separately counted each day on all selected plants (Y_1), and number of retained bolls obtained from the total daily tagged flowers on all selected plants at harvest (Y_2). As a rule, observations were recorded when the number of flowers on a given day was at least five flowers found for a population of 100 plants, and this continued for at least five consecutive days. This rule omitted eight observations in the first season and ten observations in the second season. The number of observations (n) was 68 (23 June through 29 August) and 62 (29 June through 29 August) for the two seasons, respectively. Variables of the soil moisture status considered were, the day prior to irrigation, the day of irrigation, and the first and second days after the day of irrigation. The climatic factors considered were: daily maximum air temperature (°C), minimum air temperature (°C), maximum–minimum temperature (diurnal temperature range) (°C), sunshine duration (h day^{-1}), maximum relative humidity (maxRH) (%), minimum relative humidity (minRH) (%), and wind speed (m s^{-1}), (in season II only). The maximum and minimum air temperatures were measured using mercury and alcohol thermometers, which were freely exposed to environment in louvered screens, with their bulbs at a height of 160 cm above the ground. The actual duration of bright sunshine in a day is the period calculated between sunrise and sunset. Campbell–Stokes sunshine recorders, which were suitably exposed, measured duration of sunshine. The relative humidity (%) was derived from the dry- and wet-bulb thermometer readings using Jellink's Psychometer Tables. No corrections for wind speed or atmospheric pressure were applied. Routine observations of the surface wind speed were taken at the principal synoptic hours 0600, 1200, and 1800 hours. using a Cup-anemometer whose head was freely exposed and erected at 2 m above ground. The daily mean surface wind speed was the arithmetic mean of the surface wind speed observations at the three principal synoptic hours. All the climatic factors were measured according to the methodological directions adapted by the World Meteorology Organization (WMO). The source of the climatic data was the Agricultural Meteorological Station of the Agricultural Research Station, Agricultural Research Center, Giza, Egypt. No rainfall occurred during the two growing seasons. Range and mean values of the climatic parameters (independent variables) recorded during the production stage for both seasons and overall data are listed in Table 1. Daily number of flowers and number of bolls per plant which survived to maturity (dependent variables) during the production stage in the two seasons are graphically illustrated in Figs. 1 and 2.

2.1 Basic variables

A. Dependant variables as defined above: (Y_1) and (Y_2).
B. Independent variables (X_s):

1. Irrigation on day 1=1. Otherwise, enter 0.0 (soil moisture status) (X_1)

Table 1 Range and mean values of the independent variables for the two seasons and over all data

Climatic factor's	First season[a]		Second season[b]		Over all data (two seasons)	
	Range	Mean	Range	Mean	Range	Mean
Max temp (°C)	31.0–44.0	34.3	30.6–38.8	34.1	30.6–44.0	34.2
Min temp (°C)	18.6–24.5	21.9	18.4–23.9	21.8	18.4–24.5	21.8
Max–min temp (°C)[c]	9.4–20.9	12.4	8.5–17.6	12.2	8.5–20.9	12.3
Sunshine (h day^{-1})	10.3–12.9	11.7	9.7–13.0	11.9	9.7–13.0	11.8
Max RH (%)	62–96	85.4	51–84	73.2	51–96	79.6
Min RH (%)	11–45	30.8	23–52	39.8	11–52	35.1
Wind speed (m s^{-1})	ND	ND	2.2–7.8	4.6	ND	ND

[a] Flower and boll stage (68 days, from 23 June through 29 August)

[b] Flower and boll stage (62 days, from 29 June through 29 August)

[c] Diurnal temperature range. *ND* not determined

2. The first and second days after the day of irrigation (soil moisture status) = 1. Otherwise, enter 0.0 (X_2).
3. The day prior to the day of irrigation (soil moisture status) to check for possible moisture deficiency on that day=1. Otherwise, enter 0.0 (X_3).
4. Number of days during days 1 (day of flowering)–12 (after flowering) that temperature equaled or exceeded 37.5°C (high temperature) (X_4).
5. Range of temperature (diurnal temperature) [°C] on day 1 (day of flowering) (X_5).
6. Broadest range of temperature [°C] over days 1 (day of flowering)–12 (after flowering) (X_6).
7. Minimum relative humidity (minRH) [%] during day 1 (day of flowering) (X_7).
8. Maximum relative humidity (maxRH) [%] during day 1 (day of flowering) (X_8).
9. Minimum relative humidity (minRH) [%] during day 2 (after flowering) (X_9).
10. Maximum relative humidity (maxRH) [%] during day 2 (after flowering) (X_{10}).
11. Largest maximum relative humidity (maxRH) [%] on days 3–6 (after flowering) (X_{11}).
12. Lowest minimum relative humidity (minRH) [%] on days 3–6 (after flowering) (X_{12}).
13. Largest maximum relative humidity (maxRH) [%] on days 7–12 (after flowering) (X_{13}).
14. Lowest minimum relative humidity (minRH) [%] on days 7–12 (after flowering) (X_{14}).
15. Lowest minimum relative humidity (minRH) [%] on days 50–52 (after flowering) (X_{15}).
16. Daily light period (hour) (X_{16}).

2.1.1 Statistical analysis

Simple correlation coefficients between the initial group of independent variables (climatic factors and soil moisture

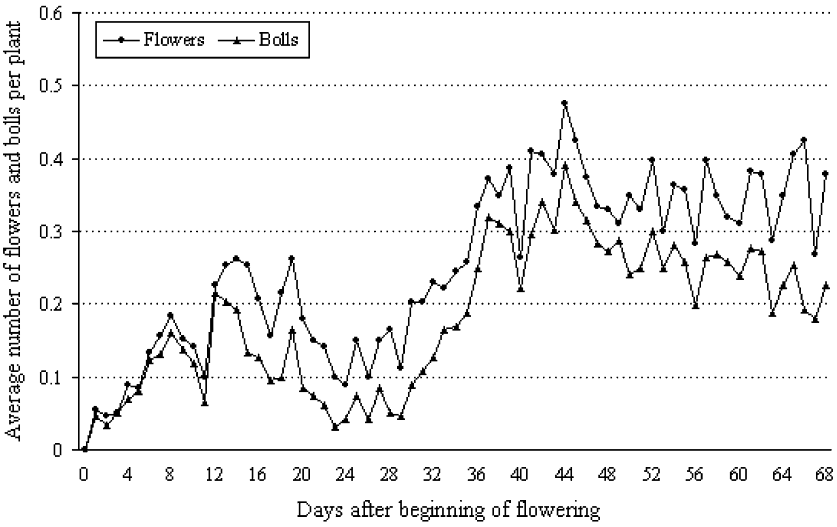

Fig. 1 Daily number of flowers and bolls during the production stage (68 days) in the first season (I) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30° N, 31°28' E), Egypt. The soil texture was a clay loam, with an alluvial substratum, (pH=8.07). Total water consumptive use during the growing season supplied by surface irrigation was about 6,000 m^3 ha^{-1}. No rainfall occurred during the growing season. The sampling size was 261 plants

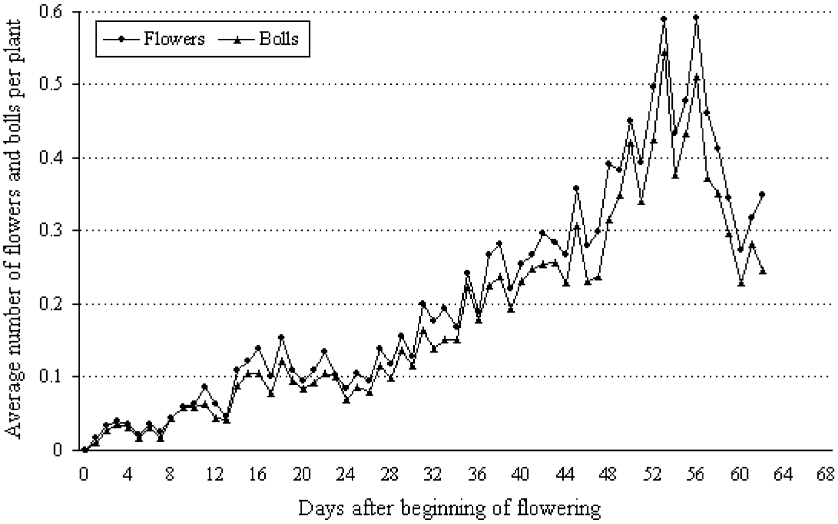

Fig. 2 Daily number of flowers and bolls during the production stage (62 days) in the second season (II) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30°N, 31°28' E), Egypt. The soil texture was a clay loam, with an alluvial substratum, (pH=8.07). Total water consumptive use during the growing season supplied by surface irrigation was about 6,000 m^3 ha^{-1}. No rainfall occurred during the growing season. The sampling size was 358 plants

status) (X's) and the corresponding dependent variables (Y's) were computed for each season and the combined data of the two seasons. These correlation coefficients helped determine the significant climatic factors and soil moisture status affecting the cotton production variables. The level for significance was $P \leq 0.15$. Those climatic factors and soil moisture status attaining a probability level of significance not exceeding 0.15 were deemed important (affecting the dependent variables). Those factors were combined with dependent variables in multiple regression analysis to obtain a predictive model as described by Cady and Allen (1972). Multiple linear regression equations (using the stepwise method) comprising selected predictive variables were computed for the determined interval. Coefficients of multiple determination (R^2) were calculated to measure the efficiency of the regression models in explaining the variation in data. Correlation and regression analysis were computed according to Draper and Smith (1966) using the procedures outlined in the general linear model (GLM) (SAS Institute 1985).

3 Results and discussion

Daily number of flowers and number of bolls per plant that survived to maturity (dependent variables) during the production stage of the two growing seasons (68 and 62 days in seasons I and II, respectively) are illustrated in Figs. 1 and 2. The flowering and boll setting curves reached their peaks during the middle 2 weeks of August and then descended until the end of the season. Specific differences in the shape of these curves in the two seasons may be due to the environmental effects on growth, for which climatic factors (Table 1) play an important role (Miller et al. 1996). The square values were determined and calculated using simple correlation coefficients with the independent variables (Y_1 and Y_2). Determinations included number of days during days 1 (day of flowering)–12 (after flowering) that temperature equaled or exceeded 37.5°C (high temperature) (X_4), minRH during day 1 (day of flowering) (X_7), maxRH during day 1 (day of flowering) (X_8), minRH humidity during day 2 (after flowering) (X_9), maxRH during day 2 (after flowering) (X_{10}), largest maxRH on days 3–6 (after flowering) (X_{11}), lowest minRH on days 3–6 (after flowering) (X_{12}), largest maxRH on days 7–12 (after flowering) (X_{13}), and lowest minRH on days 7–12 (after flowering) (X_{14}). We studied the linear curve (quadratic form) for all X variables and found no important significant effects. Wind speed data, available in the second season, showed no significant effect.

3.1 Correlation estimates

Simple correlation coefficients between the independent variables and the dependent variables for flower and boll production in each season and combined data of the two seasons are shown in Tables 2, 3, and 4. The simple correlation values indicated clearly that relative humidity was the most important climatic factor. Relative humidity also had a significant positive relationship with flower and boll production; except for lowest minRH on days 50–52 (after flowering). Flower and boll production were positive

Table 2 Simple correlation coefficient (*r*) values between the independent variables and the dependent variables in the first season (I)

Independent variables (irrigation and climatic factors)	Dependent variables (first season)	
	Flowers	Bolls
(X1) Irrigation on day 1	−0.1282	−0.0925
(X2) Irrigation on day 0 or −1 (1st and 2nd day after irrigation)	−0.1644	−0.1403
(X3) 1 is for the day prior to irrigation	−0.0891	−0.0897
(X4) Number of days that temperature equaled or exceeded 37.5°C	0.1258	0.1525
(X5) Range of temperature (°C) on day 1	−0.0270	−0.0205
(X6) Broadest range of temperature (°C) over days 1–12	0.0550	0.1788[d]
(X7) MinRH (%) during day 1	0.1492	0.1167
(X8) MaxRH (%) during day 1	0.2087[c]	0.1531
(X9) MinRH (%) during day 2	0.1079	0.1033
(X10) MaxRH (%) during day 2	0.1127	0.0455
(X11) Largest maxRH (%) on days 3–6	0.3905[a]	0.2819[b]
(X12) Lowest minRH (%) on days 3–6	0.0646	0.0444
(X13) Largest maxRH (%) on days 7–12	0.4499[a]	0.3554[b]
(X14) Lowest minRH (%) on days 7–12	0.3522[a]	0.1937[d]
(X15) Lowest minRH (%) on days 50–52	−0.3440[a]	−0.4222[a]
(X16) Daily light period (hour)	−0.2430[b]	−0.1426

[a] Significant at 1% probability level

[b] Significant at 5% probability level

[c] Significant at 10% probability level

[d] Significant at 15% probability level

and highly correlated for the variables largest maxRH (X_{11}, X_{13}) and lowest minRH (X_{14}, X_{15}) in the first season, minRH (X_7, X_9), largest maxRH (X_{11}), and lowest minRH (X_{12}, X_{14}, X_{15}) in the second season, and the combined data of the two seasons. Effect of maxRH varied markedly from the first to the second seasons. MaxRH was significantly correlated with the dependent variables in the first season, while the inverse pattern was true in the second season.

Table 3 Simple correlation coefficient (*r*) values between the independent variables and the dependent variables in the second season (II)

Independent variables (irrigation and climatic factors)	Dependent variables (second season)	
	Flowers	Bolls
(X1) Irrigation on day 1	−0.0536	−0.0467
(X2) Irrigation on day 0 or −1	−0.1116	−0.1208
(X3) 1 is for the day prior to the day of irrigation	−0.0929	−0.0927
(X4) Number of days that temperature equaled or exceeded 37.5°C	−0.4192[a]	−0.3981[a]
(X5) Range of temperature [°C] on day 1	−0.3779[a]	−0.3858[a]
(X6) Broadest range of temperature (°C) over days 1–12	−0.3849[a]	−0.3841[a]
(X7) MinRH (%) during day 1	0.4522[a]	0.4665[a]
(X8) MaxRH (%) during day 1	0.0083	0.0054
(X9) MinRH (%) during day 2	0.4315[a]	0.4374[a]
(X10) MaxRH (%) during day 2	0.0605	0.0532
(X11) Largest maxRH (%) on days 3–6	0.2486[c]	0.2520[b]
(X12) Lowest minRH (%) on days 3–6	0.5783[a]	0.5677[a]
(X13) Largest maxRH (%) on days 7–12	0.0617	0.0735
(X14) Lowest minRH (%) on days 7–12	0.4887[a]	0.4691[a]
(X15) Lowest minRH (%) on days 50–52	−0.6246[a]	−0.6113[a]
(X16) Daily light period (hour)	−0.3677[a]	−0.3609[a]

[a] Significant at 1% probability level

[b] Significant at 5% probability level

[c] Significant at 10% probability level

Table 4 Simple correlation coefficient (*r*) values between the independent variables and dependent variables in the combined two seasons (I and II)

Independent variables (irrigation and climatic factors)	Dependent variables (Combined two seasons)	
	Flowers	Bolls
(X1) Irrigation on day 1	−0.0718	−0.0483
(X2) Irrigation on day 0 or −1	−0.1214	−0.1108
(X3) 1 is for the day prior to the day of irrigation	−0.0845	−0.0769
(X4) Number of days that temperature equaled or exceeded 37.5°C	−0.2234[b]	−0.1720[c]
(X5) Range of temperature (°C) on day 1	−0.2551[a]	−0.2479[a]
(X6) Broadest range of temperature (°C) over days 1–12	−0.2372[a]	−0.1958[b]
(X7) MinRH (%) during day 1	0.3369[a]	0.3934[a]
(X8) MaxRH (%) during day 1	0.0032	−0.0911
(X9) MinRH (%) during day 2	0.3147[a]	0.3815[a]
(X10) MaxRH (%) during day 2	−0.0094	−0.1113
(X11) Largest maxRH (%) on days 3–6	0.0606	−0.0663
(X12) Lowest minRH (%) on days 3–6	0.3849[a]	0.4347[a]
(X13) Largest maxRH (%) on days 7–12	−0.0169	−0.1442[d]
(X14) Lowest minRH (%) on days 7–12	0.3891[a]	0.4219[a]
(X15) Lowest minRH (%) on days 50–52	−0.3035[a]	−0.2359[a]
(X16) Daily light period (hour)	−0.3039[a]	−0.2535[a]

[a] Significant at 1% probability level

[b] Significant at 5% probability level

[c] Significant at 10% probability level

[d] Significant at 15% probability level

This diverse effect may be best explained by the differences of 87% in the first season, and only 73% in the second season (Table 1). Also, when the average value of minRH exceeded the half average value of maxRH, the minRH can substitute for the maxRH on affecting number of flowers or harvested bolls. In the first season (Table 1), the average value of minRH was less than half of the value of maxRH (30.2/85.6=0.35), while in the second season, it was higher than half of maxRH (39.1/72.9=0.54). Sunshine duration (X_{16}) showed a significant negative relation with fruit production in the first and second seasons and the combined data of the two seasons except for boll production in the first season, which was not significant. Flower and boll production were negatively correlated in the second season and the combined data of the two seasons for the number of days during days 1–12 that temperature equaled or exceeded 37.5°C (X_4), range of temperature (diurnal temperature) on flowering day (X_5), and broadest range of temperature over days 1–12 (X_6). The soil moisture status showed low and insignificant correlation to flower and boll production. The positive relationship between relative humidity with flower and boll production means that low relative humidity rate reduces significantly cotton flower and boll production. This may be due to greater plant water deficits when relative humidity decreases. Also, the negative relationship between the variables of maximum temperature exceeding 37.5°C (X_4), range of diurnal temperature on flowering (X_5), and sunshine duration (X_{16}) with flower and boll production revealed that the increased values of these factors had a detrimental effect upon Egyptian cotton fruit production. Results obtained from the production stage of each season and the combined data of the two seasons showed marked variability in the relationships of some climatic variables with the dependent variables. This may be best explained by the differences between climatic factors in the two seasons as illustrated by the ranges and means shown in Table 1. For example, maximum temperature exceeding 37.5°C (X_4) and minRH did not show significant relations in the first season, while that trend differed in the second season.

These results indicated that relative humidity was the most effective and consistent climatic factor affecting boll production. As the sign of the relationship was positive, this means that the sensible decrease in relative humidity would cause a significant reduction in boll number. Thus, applying specific practices such as an additional irrigation and the use of plant growth regulators should decrease the deleterious effect of evaporation after boll formation and hence contribute to an increase in cotton boll production and retention and cotton yield. Moseley et al. (1994) stated that methanol has been reported to increase water use efficiency, growth, and development of C_3 plants in arid conditions, under intense sunlight. In field trials, cotton cv. DPL-50 (*Gossypium hirsutum*) was sprayed with a nutrient solution (1.33 lb N+0.27 lb Fe+0.27 lb Zn acre^{-1}) or 30% methanol solution at a rate of 20 gallons acre^{-1} or sprayed with both the nutrient solution and methanol under two soil moisture regimes (irrigated and dry land). The foliar spray treatments were applied six times during the growing season beginning at first bloom. They found that irrigation (a total of 4.5 in. applied in July) increased lint yield across foliar spray treatments by 18%. They concluded that PGR-IV can partially alleviate the detrimental effects of water stress on photosynthesis and dry matter accumulation and improves the growth and nutrient absorption of growth chamber-grown cotton plants.

The second most important climatic factor in our study was sunshine duration, which showed a significant negative relationship with boll production. The negative relationship between sunshine duration and cotton production might be due to the fact that the species of the genus *Gossypium* are known to be short-day plants (Hearn and Constable 1984). Thus, an increase in sunshine duration above that sufficient to attain good plant growth will decrease flower and boll production. Bhatt (1977) found that exposure to daylight over 14 h and high day temperature, individually or in combination, delayed flowering of the Upland cotton cv. J 34. The average sunshine duration in the present study was only 11.7 h, which in combination with high maximum temperatures (up to 44°C) may have had an adverse effect on flower and boll formation.

The factors in this study, which had been found to be associated with boll development, are the climatic factors that would influence water loss between plant and atmosphere (high relative humidity and shorter solar duration). This can lead to direct effects on the fruiting forms themselves and inhibitory effects on mid-afternoon photosynthetic rates even under well-watered conditions. Boyer et al. (1980) found that soybean plants with ample water supplies can experience water deficits due to high transpiration rates. Also, Human et al. (1990) stated that, when sunflower plants were grown under controlled temperature regimes and water stress during budding, anthesis, and seed filling, the CO_2 uptake rate per unit leaf area as well as total uptake rate per plant, significantly diminished with stress, while this effect resulting in a significant decrease in yield per plant.

3.2 Multiple linear regression models, beside contribution of climatic factors and soil moisture status to variations in the dependent variables

Regression models were established using the stepwise multiple regression technique to express the relationship between the number of flowers and bolls per plant^{-1} (Y) with the climatic factors and soil moisture status (Table 5). Relative humidity (%) was the most important climatic factor affecting flower and boll production in Egyptian cotton [minRH during day 1 (X_7), minRH during day 2 (X_9), largest maxRH on days 3–6 (X_{11}), lowest minRH on days 3–6 (X_{12}), largest maxRH on days 7–12 (X_{13}), lowest minRH on days 7–12 (X_{14}), and lowest minRH on days 50–52 (X_{15})]. Sunshine duration (X_{16}) was the second climatic factor of importance affecting production of flowers and bolls. Maximum temperature (X_4), broadest range of temperature (X_6), and soil moisture status (X_1) made a contribution affecting flower and boll production. The soil moisture variables (X_2, X_3), and climatic factors (X_5, X_8, X_{10}) were not included in the equations, since they had very little effect on production of cotton flowers and bolls.

Relative humidity showed the highest contribution to the variation in both flower and boll production (Table 5). This finding can be explained in the light of results found by Ward and Bunce (1986) in sunflower (*Helianthus annuus*). They stated that decreases of relative humidity on both leaf

Table 5 Model obtained for cotton production variables as functions of climatic data and soil moisture status in individual and combined seasons

Season	Model	R^2
Season I (n=68)	$Y_1=-557.54+6.35X_6+0.65X_7+1.92X_{11}+4.17X_{13}+2.88X_{14}-1.90X_{15}-5.63X_{16}$	0.63
	$Y_2=-453.93+6.53X_6+0.61X_7+1.80X_{11}+2.47X_{13}+1.87X_{14}-1.85X_{15}$	0.53
Season II (n=62)	$Y_1=-129.45+25.36X_1+37.02X_4+1.48X_7+1.69X_9+4.46X_{12}+2.55X_{14}-4.73X_{15}$	0.72
	$Y_2=-130.23+24.27X_1+35.66X_4+1.42X_7+1.61X_9+4.00X_{12}+2.18X_{14}-4.09X_{15}$	0.71
Combined data: I and II (n=130)	$Y_1=-557.36+6.82X_6+1.44X_7+0.75X_9+2.04X_{11}+2.55X_{12}+2.01X_{13}+3.27X_{14}-2.15X_{15}$	0.57
	$Y_2=-322.17+6.41X_6+1.20X_7+0.69X_9+1.81X_{11}+2.12X_{12}+2.35X_{14}-2.16X_{15}$	0.53

All entries significant at 1% level. (Y_1) Number of cotton flowers; (Y_2) Number of cotton bolls. (X_1) Irrigation on day 1; (X_4) Number of that temperature equaled or exceeded 37.5°C; (X_6) Broadest range of temperature [°C] over days 1–12; (X_7) MinRH [%] during day 1; (X_9) MinRH [%] during day 2; (X_{11}) Largest maxRH [%] on days 3–6; (X_{12}) Lowest minRH [%] on days 3–6; (X_{13}) Largest maxRH [%] on days 7–12; (X_{14}) Lowest minRH [%] on days 7–12; (X_{15}) Lowest minRH [%] on days 50–52; (X_{16}) Daily light period (hour).

surfaces reduced photosynthetic rate of the whole leaf for plants grown under a moderate temperature and medium light level. Kaur and Singh (1992) found in cotton that flower number was decreased by water stress, particularly when applied at flowering. Seed cotton yield was reduced by almost 50% due to water stress applied at flowering, slightly decreased by stress at boll formation, and not significantly affected by stress in the vegetative stage (6–7 weeks after sowing). Orgaz et al. (1992) in field experiments at Cordoba, SW Spain, grew cotton cvs. Acala SJ-C1, GC-510, Coker-310, and Jean at evapotranspiration (ET) levels ranging from 40% to 100% of maximum ET (ET_{max}), which were generated with sprinkler line irrigation. The water production function of cv. Jean was linear; seed yield was 5.30 t ha^{-1} at ET_{max} (820 mm). In contrast, the production function of the three other cultivars was linear up to 85% of ET_{max}, but leveled off as ET approached ET_{max} (830 mm) because a fraction of the set bolls did not open by harvest at high ET levels. These authors concluded that it is possible to define an optimum ET deficit for cotton based on cultivar earliness, growing-season length, and availability of irrigation water.

Several researchers referred to the effect of climatic factors on cotton flower, boll production, and yield. Mergeai and Demol (1991) in phytotron trials in Belgium found that cotton yield was favored by intermediate relative humidity (60%) and temperatures of 24–28°C. Under long photoperiods (16 h), low night temperature (12°C) increased vegetative growth and cotton yields, but under short photoperiods (12 h), yields were better with a higher night temperature (16°C).

Reddy et al. (1991) found that the number of fruiting sites per plant increased linearly as temperature increased to 30°C/22°C (day/night temperature regimes), but declined by over 50% at 35°C/27°C. Plants grown at 40°C/32°C did not produce reproductive structures during the entire 64 DAE (days after emergence) period. Optimum temperature for reproductive growth in Pima cotton in terms of number of fruiting branches, length, and nodes per branch was 30°C/22°C, and this was also the optimum temperature for flower bud and boll production and retention. More flower buds and bolls were aborted at 35°C/27°C than at the optimum or lower temperature. Plants grown at 40°C/32°C remained vegetative during the 64 DAE periods.

Hodges et al. (1993) found that cotton (*Gossypium hirsutum*) fruit retention decreased rapidly as the time of exposure to 40°C increased. Warner and Burke (1993) indicated that the cool-night inhibition of cotton (*Gossypium hirsutum)* growth is correlated with biochemical limitation on starch mobilization in source leaves, which result in a secondary inhibition of photosynthesis, even under optimal temperature during the day. Wang and Whisler (1994) found that climatic factors resulting in maximum cotton yield in Mississippi were: maximum temperature −1% (below the average); minimum temperature was 0% to 5% (above the average); solar radiation was −10% (below the average); wind speed was −10% or +25% (below or above the average) and rainfall was +1 in. (above the average). Reddy et al. (1995b) observed that when cotton cv DPL-50 plants grown in growth chambers were exposed for 70 days to natural light levels with average temperature of 17.8°C, 18.7°C, 22.7°C, 26.6°C, or 30.6°C, number of squares and bolls produced were increased with increased temperature up to 30.6°C. Reddy et al. (1996) observed that when cotton cv DPL-51 (Upland cotton) was grown in controlled environments with natural solar radiation, flower and fruit retention was very low at an ambient temperature from 31.3°C to 33°C. They concluded that the grower could minimize boll abscission where high temperature and low relative humidity occur by growing heat-tolerant cultivars, proper management of planting date, adequate fertilization, optimum plant density, and applying suitable irrigation regime which would avoid drought stress. Gutiérrez Mas and López (2003) studied the effects of heat on the yields of cotton in Andalucia, Spain, during 1991–1998, and found that high temperatures were implicated in the reduction of unit production. There was a significant negative relationship between average production and number of days with temperatures greater than 40°C and the number of days with minimum temperatures greater than 20°C. Wise et al. (2004) indicated that restrictions to photosynthesis could limit plant growth at high temperature in a variety of ways. In addition to increasing photorespiration, high temperatures (35–42°C) can cause direct injury to the photosynthetic apparatus. Both carbon metabolism and thylakoid reactions have been suggested as the primary site of injury at these temperatures.

Regression models obtained explained a sensible proportion of the variation in flower and boll production, as indicated by their R^2, which ranged between 0.53 and 0.72. These results agree with Miller et al. (1996) in their regression study of the relation of yield with rainfall and temperature. They suggested that the other R^2 0.50 of variation related to management practices, which coincide with those in this study. Thus, an accurate climatic forecast for the effect of the 5- to 7-day period during flowering may provide an opportunity to avoid possible adverse effects of unusual climatic conditions before flowering or after boll formation by utilizing additional treatments and/or adopting proper precautions to avoid flower and boll reduction.

Temperature conditions during the reproduction growth stage of cotton in Egypt do not appear to limit growth even though they are above the optimum for cotton growth. This is contradictory to the finding of Holaday et al. (1997). A possible reason for that contradiction is that the effects of soil moisture status and relative humidity were not taken into consideration in the research studies conducted by other researchers in other countries. Since temperature and evaporation are closely related to each other, the higher evaporation rate could possible mask the effect of temperature. Sunshine duration and minimum relative humidity appeared to have secondary effects, yet they are in fact important factors. The importance of sunshine duration has been alluded to by Moseley et al. (1994) and Oosterhuis (1997). Mergeai and Demol (1991) found that cotton yield was associated with intermediate relative humidity.

In contrast other researchers found that temperature was often the major factor affecting cotton growth. In this respect, Burke et al. (1988) defined the thermal kinetic window (TKW) as the optimum temperature range for biochemical and metabolic activities of plants (a temperature range that permits normal enzyme functions in plants). The TKW for cotton growth is 23.5°C to 32°C, with an optimum temperature of 28°C. Plant temperature above or below the TKW resulted in stress that limited growth and yield. Holaday et al. (1997) in growth chamber experiments with cotton cv. Coker 312 showed that cool night times (15°C or 19°C) reduced photosynthetic efficiency compared with warm night times (28°C). This is ascribed to reducing stomata conductance, resulting in lower sucrose levels during the day and reduced ability to export sucrose from the leaf, to storage places. Oosterhuis (1997) reported that the reason for low and variable cotton yields in Arkansas is the unusually high insect pressures and the development of the boll load during an exceptionally hot/dry August. Suggested solutions to these problems were selection of tolerant cultivars, effective and timely insect and weed control, adequate irrigation regime, use of proper crop monitoring techniques and application of plant growth regulators. Under mild water stress, Meek et al. (1999) found that the application of 3 or 6 kg glycine betaine (PGR) ha^{-1} increased yields. Reddy et al. (1998) found that when Upland cotton (*G. hirsutum*) cv. DPL-51 was grown in naturally lit plant growth chambers at 30°C/22°C day/night temperatures from sowing until floral bud production, and at 20°C/12°C, 25°C/17°C, 30°C/22°C, 35°C/27°C, and 40°C/32°C for 42 days after floral bud production, fruit retention was severely curtailed at the two higher temperatures. Species/cultivars that retain fruits at high temperatures would be more productive both in the present-day cotton production environments and even more so in a future warmer world.

4 Conclusions

From the results obtained in the present study, it could be generally concluded that relative humidity, high temperature, and sunshine duration were the most significant climatic factors affecting cotton flower and boll production and retention in Egyptian cotton. The positive correlation between the minRH value along with the negative correlation between each of high air temperature and sunshine duration with flower and boll formation, indicate that high value of minRH, short period of sunshine duration, and low value of temperature would enhance flower and boll formation. Temperature appeared to be less important in the reproduction growth stage of cotton in Egypt than minRH (water stress) and sunshine duration. These findings concur with those of other researchers, except for the importance of temperature. A possible reason for that contradiction is that the effects of evaporation rate and relative humidity were not taken into consideration in the research studies conducted by other researchers in other countries. Since temperature and evaporation are closely related to each other, the higher evaporation rate could possible mask the effect of temperature. In conclusion, the early prediction of possible adverse effects of climatic factors might modify their effect on production of Egyptian cotton. Minimizing deleterious effects through the application of management practices, such as adequate irrigation regime (Orgaz et al. 1992; Oosterhuis 1997), and utilization of specific plant growth regulators (Moseley et al. 1994; Zhao and Oosterhuis 1997; Meek et al. 1999) could limit the negative effects of some climatic factors.

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