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Research Paper

Climatic variables and cotton production: Studying the nature of its relationships by different statistical and mathematical methods

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ABSTRACT

Cotton yield is a function of growth rates, flower production rates, and flower and boll retention during the fruiting period. Information on the relationship between climatic factors and the cotton plant's ability to produce and sustain flower buds, flowers and bolls will allow one to model plant responses to conditions that frequently occur in the field and to predict developmental rate or the formation of these organs. Understanding the impacts of climatic factors on cotton production may help physiologists to determine the control mechanisms of boll retention in cotton. However, weather 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. The early prediction of possible adverse effects of climatic factors might modify their effect on production of cotton. This study investigates the statistical relationship between various climatic factors, overall flower and boll production and also provides information on the effect of various climatic factors and soil moisture status during the development stage on flower and boll production in cotton. Evaporation, sunshine duration, relative humidity, surface soil temperature at 1800 h, and maximum air temperature are the important climatic factors that significantly affect flower and boll production. There was a negative correlation between flower and boll production and either evaporation or sunshine duration, while correlation with minimum relative humidity was positive.

Key words: Cotton flower and boll production, evaporation, relative humidity, soil moisture status, sunshine duration, temperature.

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INTRODUCTION

Climate affects crop growth interactively, sometimes resulting in unexpected responses to prevailing conditions. Many factors, such as length of the growing season, climate (including solar radiation, temperature, light, wind, rainfall and dew), cultivar, availability of nutrients and soil moisture, pests and cultural practices affect cotton growth (El-Zik, 1980). 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 (Sawan, 2013).

Water is a primary factor controlling plant growth. 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 also increased leaf temperature and specific leaf area.

Temperature is also a primary factor controlling rates of plant growth and development. Burke et al. (1988) 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 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. Sawan (2013) found that the optimum temperature for cotton stem and leaf growth, seedling development and fruiting was almost 30°C, with fruit retention decreasing rapidly as the time of exposure to 40°C increased. Reddy et al. (1998) found that when upland cotton (*Gossypium hirsutum*) cv. DPL-51 was grown in naturally lit plant growth chambers at 30/22°C day/night temperatures from sowing until flower bud production, and at 20/12, 25/17, 30/22, 35/27 and 40/32°C for 42 days after flower bud production, fruit retention was severely curtailed at the two higher temperatures compared with 30/22°C. Species/cultivars that retain fruits at high temperatures would be more productive both in the present-day cotton production environments and even more in future warmer world. Schrader et al. (2004) stated that high temperature plants are likely to experience inhibit photosynthesis.

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 (node 7 to 9) and top (node 10) bolls, especially for double cropping patterns with early maturing varieties.

Objectives of this study

The objectives of this investigation were to study:

1) The effect of various climatic factors on the overall flower and boll production in Egyptian cotton. This could pave the way for formulating advanced predictions for the effect of certain climatic conditions on cotton production of Egyptian cotton. It would be useful to minimize the deleterious effects of the factors through utilizing proper cultural practices which would limit and control their negative effects and this will lead to an increase in cotton yield.
2) Provide information on 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 for 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.

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 of 19 m), using the cotton cultivar Giza 75 (*G barbadense* L.) in 2 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) (Sawan et al., 2010).

In Egypt, there are no rain-fed areas for cultivating cotton. Water for the field trials was applied using surface irrigation. Total water consumed during each of the 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 to 60 cm). In season I, the field was irrigated on 15th March (at planting), 8th April (first irrigation), 29th April, 17th May, 31st May, 14th June, 1st July, 16th July, and 12th August. In season II, the field was irrigated on 23rd March (planting date), 20th April (first irrigation), 8th May, 22nd May, 1st June, 18th June, 3rd July, 20th July, 7th August and 28th 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 15th and 23rd March in seasons I and II, respectively, in hills 20 cm apart on one side of the ridge. Seedlings were thinned to 2 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 was applied after thinning just before the second irrigation and the second was applied before the third irrigation. Rates of phosphorus, potassium and nitrogen fertilizers were the same in both seasons. These amounts were determined based on the use of soil tests (Sawan et al., 2010).

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 9 and 11 inner ridges of the plot in seasons I and II respectively. Pest control management was carried out on an-as-needed basis, according to the local practices performed at the experimental plot.

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

Climatic factors	First season*		Second season**		Overall data (Two seasons)	
	Range	Mean	Range	Mean	Range	Mean
Maximum temperature (°C), (X_1)	31.0-44.0	34.3	30.6-38.8	34.1	30.6-44.0	34.2
Minimum temperature (°C), (X_2)	18.6-24.5	21.9	18.4-23.9	21.8	18.4-24.5	21.8
Max-Min temperature (°C), (X_3)♦	9.4-20.9	12.4	8.5-17.6	12.2	8.5-20.9	12.3
Evaporation (mm d^{-1}), (X_4)	7.6-15.2	10.0	4.1-9.8	6.0	4.1-15.2	8.0
0600 h Temp (°C), (X_5)	14.0-21.5	17.8	13.3-22.4	18.0	13.3-22.4	17.9
1800 h Temp (°C), (X_6)	19.6-27.0	24.0	20.6-27.4	24.2	19.6-27.4	24.1
Sunshine (h d^{-1}), (X_7)	10.3-12.9	11.7	9.7-13.0	11.9	9.7-13.0	11.8
MaxRH (%), (X_8)	62-96	85.4	51-84	73.2	51-96	79.6
MinRH (%), (X_9)	11-45	30.8	23-52	39.8	11-52	35.1
Wind speed (m s^{-1}), (X_{10})	ND	ND	2.2-7.8	4.6	ND	ND

♦Diurnal temperature range; ND not determined; *Flower and boll stage (68 days, from 23 June through 29 August). **Flower and boll stage (62 days, from 29 June through 29 August) (Sawan et al., 2010).

Flowers on all selected plants were tagged in order to count and record the number of open flowers and bolls set on a daily basis. The flowering season commenced on the date of the first flower appearance and continued until the end of flowering season (31st August). The entire month of September (30 days) until the 20th of October (harvest date) allowed a minimum of 50 days to develop mature bolls. In season I, the flowering period extended from 17th June to 31st August, whereas in season II, the flowering period was from 21st June to 31st August. Flowers produced after 31st 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), number of retained bolls obtained from the total daily tagged flowers on all selected plants at harvest (Y_2), and (Y_3) percentage of boll retention ([number of retained bolls obtained from the total number of daily tagged flowers in all selected plants at harvest]/[daily number of tagged flowers on each day in all selected plants] × 100).

As a rule, observations were recorded when the number of flowers on a given day was at least 5 flowers found in 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 (23rd June through 29th August) and 62 (29th June through 29th August) for the two seasons, respectively. Variables of the soil moisture status considered were days prior to irrigation, day of irrigation, and the first and second days after the day of irrigation (Sawan et al., 2010).

The climatic factors (independent variables) considered were daily data of: maximum air temperature (°C, X_1); minimum air temperature (°C, X_2); maximum-minimum air temperature (diurnal temperature range) (°C, X_3); evaporation (expressed as Piche evaporation) (mm day^{-1}, X_4); surface soil temperature, grass temperature or green cover temperature at 0600 h (°C, X_5) and 1800 h (°C, X_6); sunshine duration (h day^{-1}, X_7);

maximum relative humidity (maxRH) (%, X_8), minimum relative humidity (minRH) (%, X_9) and wind speed (m s^{-1}, X_{10}) in season II only. 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.

Daily records of the climatic factors (independent variables) were taken for each day during production stage. Range and mean values of the climatic parameters recorded during the production stage for both seasons and overall data are listed in Table 1 (Sawan et al., 2010). Daily number of flowers and number of bolls per plant which survived till maturity (dependent variables) during the production stage in the two seasons are graphically illustrated in Figures 1 and 2 (Sawan et al., 2010).

RESULTS AND DISCUSSION

Response of flower and boll development to climatic factors on the anthesis day

Daily number of flowers and number of bolls per plant which survived to maturity (dependent variables) during the production stage of the two seasons (68 and 62 days in the first and the second seasons, respectively) are graphically illustrated in Figures 1 and 2 (Sawan et al., 2010). The flower- and boll-curves reached their peaks during the middle two weeks of August, and then descended steadily till the end of the season. Specific differences in the shape of these curves in the two seasons may be due to the growth-reactions of environment, where climatic factors (Table 1) (Sawan et al., 2010) represent an important part of the environmental effects (Miller et al., 1996).

Correlation estimates

Results of correlation coefficients [correlation and

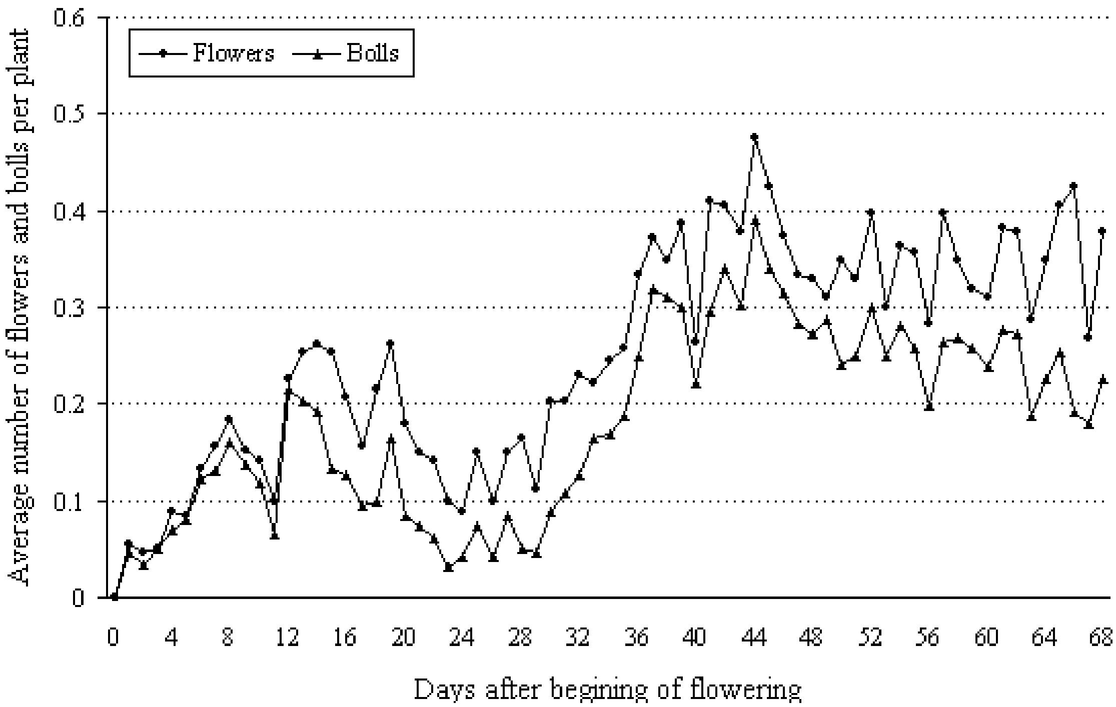

Figure 1: Daily number of flowers and bolls during the production stage (68 days) in the first season (I) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30°N, 31°:28'E), Egypt. The soil 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 6000 m^3ha^{-1}. No rainfall occurred during the growing season. The sampling size was 261 plants (Sawan et al., 2010).

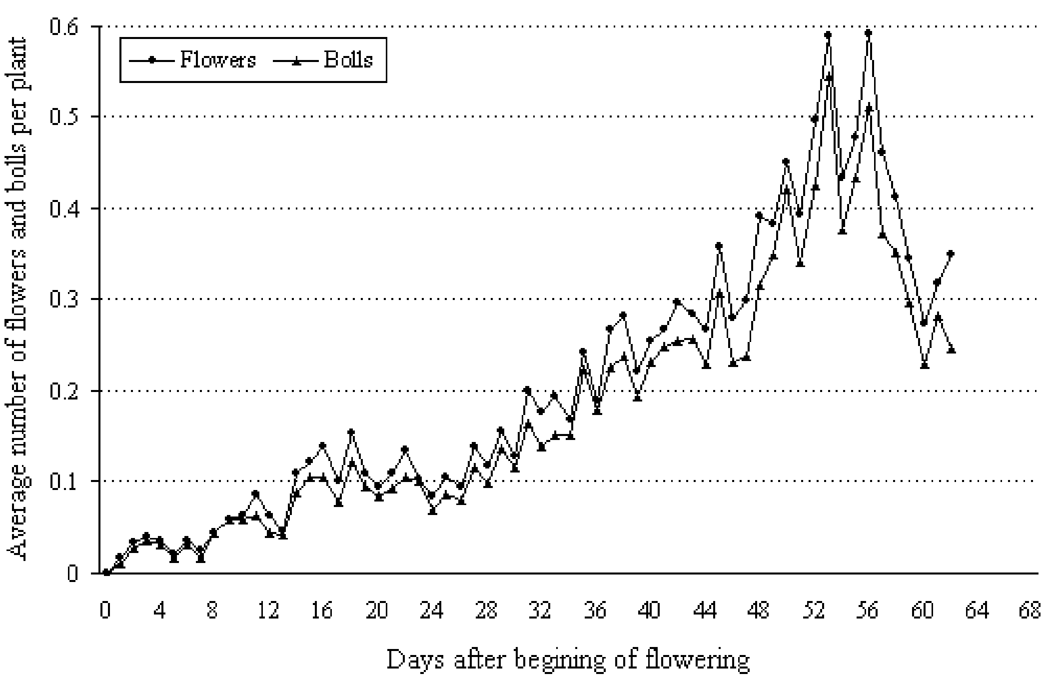

Figure 2: Daily number of flowers and bolls during the production stage (62 days) in the second season (II) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30°N, 31°:28'E), Egypt. The 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 6000 m^3ha^{-1}. No rainfall occurred during the growing season. The sampling size was 358 plants (Sawan et al., 2010).

Table 2: Simple correlation values for the relationships between the independent variables and the studied dependent variable.

Independent variables (Climatic factors)	Dependent variable					
	First season		Second season		Combined data	
	Flower	Boll	Flower	Boll	Flower	Boll
Maximum temperature [°C] (X_1)	−0.07	−0.03	−0.42**	−0.42**	−0.27**	−0.26**
Minimum temperature [°C] (X_2)	−0.06	−0.07	0.00	0.02	−0.03	−0.02
Max-Minimum temperature [°C] (X_3)	−0.03	−0.01	−0.36**	−0.37**	−0.25**	−0.24**
Evaporation [mm d^{-1}] (X_4)	−0.56**	−0.53**	−0.61**	−0.59**	−0.40**	−0.48**
0600 h temperature [°C] (X_5)	−0.01	−0.06	−0.14	−0.13	−0.09	−0.09
1800 h temperature [°C] (X_6)	−0.02	−0.16	−0.37**	−0.36**	−0.27**	−0.25**
Sunshine [h d^{-1}] (X_7)	−0.25*	−0.14	−0.37**	−0.36**	−0,31**	−0.25**
Maximum RH [%] (X_8)	0.40**	0.37**	0.01	0.01	0.04	−0.06
Minimum RH [%] (X_9)	0.14	0.10	0.45**	0.46**	0.33**	0.39**
Wind speed [m s^{-1}] (X_{10})	ND	ND	−0.06	−0.04	ND	ND

ND not determined; * $P < 0.05$; ** $P < 0.01$ (Sawan et al., 2002).

and Smith (1966) by means of the computer program SAS package (SAS Institute, 1985) between the initial group of independent variables and each of the flower and boll production in the first and second seasons. Table 2 shows the combined data of the two seasons (Sawan et al., 2002).

The correlation values indicate clearly that evaporation is the most important climatic factor affecting flower and boll production as it showed the highest correlation value. This factor had a significant negative relationship with flower and boll production. Sunshine duration showed a significant negative relation with fruit production except for boll production in the first season, which was not significant. Maximum air temperature, temperature magnitude and surface soil temperature at 1800 h were also negatively correlated with flower and boll production in the second season and the combined data of the two seasons. Minimum humidity in the second season, the combined data of the two seasons, and maximum humidity in the first season were positively and highly correlated with flower and boll production. Minimum air temperature and soil surface temperature at 0600 h showed low and insignificant correlation to flower and boll production (Sawan et al., 2002).

The negative relationship between evaporation with flower and boll production, means that high evaporation rate significantly reduces cotton flower and boll production. This may be due to greater plant water deficits when evaporation increases. Also, the negative relation between each of maximum temperature, temperature magnitude, surface soil temperature at 1800 h, or sunshine duration, with flower and boll production revealed that the increase in the values of these factors had a detrimental effect upon fruit production in Egyptian cotton. On the other hand, there was a positive correlation between each of maximum or minimum humidity with flower and boll production (Sawan et al., 2002).

Results obtained from the production stage of each season individually and the combined data of the two seasons indicate that relationships of some climatic variables with the dependent variables varied markedly from one season to another. This may be due to the differences between climatic factors in the two seasons as illustrated by the ranges and means shown in Table 1 (Sawan et al., 2010). For example, maximum temperature, minimum humidity and soil surface temperature at 1800 h did not show significant relations in the first season, while that trend differed in the second season. The effect of maximum humidity varied markedly from the first season to the second where it was significantly correlated with the dependent variables in the first season, while the inverse pattern was true in the second season. This diverse effect may be due to the differences in the mean values of this factor in the two seasons; where it was, on average, about 86% in the first season, and about 72% on average in the second season (Table 1) (Sawan et al., 2010).

Boll retention ratio [(The number of retained bolls obtained from the total number of each daily tagged flowers in all selected plants at harvest/Total number of daily tagged flowers of all selected plants) × 100] curves for both of the two seasons are shown in Figures 3 and 4 (Sawan et al., 2002). Also, these curves describe why the shapes and patterns associated with the flower and boll curves for I and II seasons were different. It seems reasonable that the climatic data that were collected in these two experiments (I and II seasons) could provide adequate information for describing how these two seasons differed and how the crop responded accordingly (Sawan, 2014, 2016).

These results indicate that evaporation is the most effective and consistent climatic factor affecting boll production. As the sign of the relationship was negative, this means that an increase in evaporation would cause a significant reduction in boll number. Thus, applying specific treatments such as an additional irrigation, and use of plant growth regulators would decrease the deleterious effect of

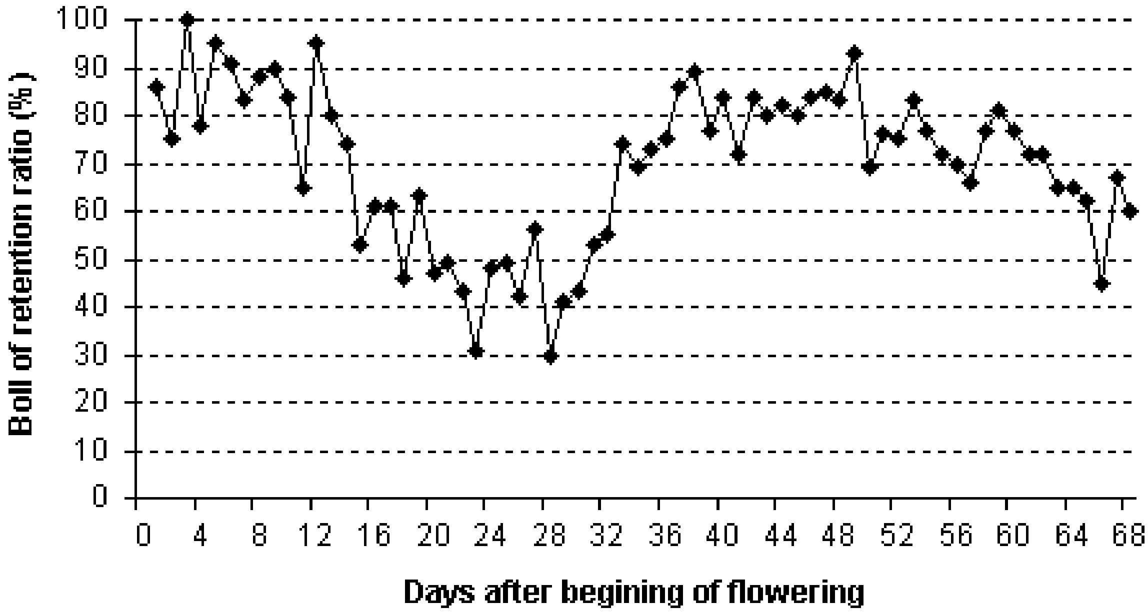

Figure 3: Daily boll retention ratio during the production stage (68 days) in the first season (I) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30°N, 31°:28'E at an altitude 19 m), 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 6000 m^3 ha^{-1}. No rainfall occurred during the growing season. The sampling size was 261 plants (Sawan et al., 2002).

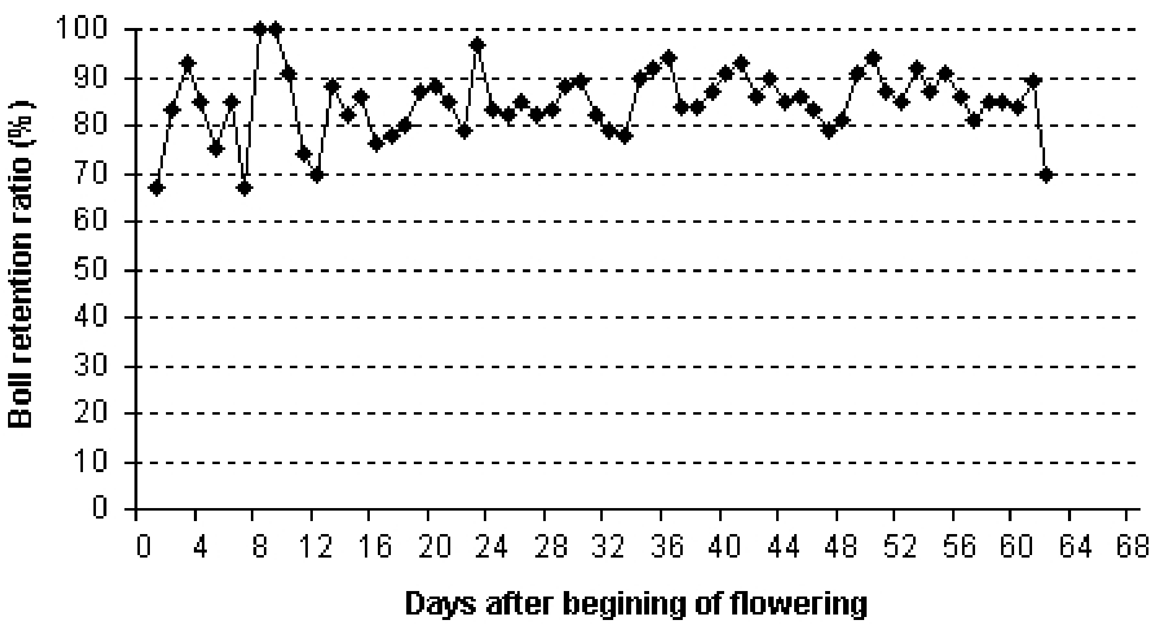

Figure 4: Daily boll retention ratio during the production stage (62 days) in the second (II) for the Egyptian cotton cultivar Giza 75 (*Gossypium barbadense* L.) grown in uniform field trial at the experimental farm of the Agricultural Research Centre, Giza (30°N, 31°:28'E at an altitude 19 m), Egypt. 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 6000 m^3 ha^{-1}. No rainfall occurred during the growing season. The sampling size was 358 plants (Sawan et al., 2002).

evaporation after boll formation and hence, contribute to an increase in cotton boll production and retention, and the consequence is an increase in cotton yield (Sawan et al., 2002). In this connection, 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 (*G 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 inches applied in July) increased lint yield across foliar spray treatments by 18%. Zhao and Oosterhuis (1997) reported that in a growth chamber when cotton (*G hirsutum* cv. Stoneville 506) plants were treated with the plant growth regulator PGR-IV (gibberellic acid, IBA and a proprietary fermentation broth) under water deficit stress a significant higher dry weights of roots and floral buds than the untreated water-stressed plants was observed. They concluded that PGR-IV can partially alleviate the detrimental effects of water stress on photosynthesis and dry matter accumulation and improve the growth and nutrient absorption of growth chamber-grown cotton plants. Meek et al. (1999) in a field experiment in Arkansas found that application of 3 or 6 kg glycine betaine (PGR) ha^{-1}, to cotton plants had the potential for increasing yield in cotton exposed to mild water stress.

Multiple linear regression equation

By means of the multiple linear regression analysis, fitting predictive equations (having good fit) were computed for flower and boll production per plant using selected significant factors from the nine climatic variables studied in this investigation. Wind speed evaluated during the second season had no influence on the dependent variables. The equations obtained for each of the two dependent variables, that is, number of flowers (Y_1) and bolls per plant (Y_2) in each season and for combined data from the two seasons (Table 2) (Sawan et al., 2002) are as follows:

First season: (n = 68)
$Y_1 = 21.691 - 1.968\ X_4 - 0.241\ X_7 + 0.216\ X_8$, R = 0.608** and $R^2 = 0.3697$, while R^2 for all studied variables was 0.4022.
$Y_2 = 15.434 - 1.633\ X_4 + 0.159\ X_8$, R = 0.589** and $R^2 = 0.3469$ and R^2 for all studied variables was 0.3843.

Second season: (n = 62)
$Y_1 = 77.436 - 0.163\ X_1 - 2.861\ X_4 - 1.178\ X_7 + 0.269\ X_9$, R = 0.644**, $R^2 = 0.4147$.
$Y_2 = 66.281 - 0.227X_1 - 3.315X_4 - 2.897X_7 + 0.196X_9$, R = 0.629**, $R^2 = 0.3956$.

In addition, R^2 for all studied variables was 0.4503 and 0.4287 for Y_1 and Y_2 equations respectively.

Combined data for the two seasons: (n = 130)
$Y_1 = 68.143 - 0.827\ X_4 - 1.190\ X_6 - 2.718\ X_7 + 0.512\ X_9$, R = 0.613**, $R^2 = 0.3758$;
$Y_2 = 52.785 - 0.997\ X_4 - 0.836\ X_6 - 1.675\ X_7 + 0.426\ X_9$, R = 0.569**, $R^2 = 0.3552$.
While R^2 for all studied variables was 0.4073 for Y_1 and 0.3790 for Y_2.

Three climatic factors, that is, minimum air temperature, surface soil temperature at 0600 h, and wind speed were not included in the equations since they had very little effect on production of cotton flowers and bolls. The sign of the partial regression coefficient for an independent variable (climatic factor) indicates its effect on the production value of the dependent variable (flowers or bolls). This means that high rates of humidity and/or low values of evaporation will increase fruit production (Sawan et al., 2002).

Contribution of selected climatic factors to variations in the dependent variable

Table 3 shows the relative contributions (RC %) for each of the selected climatic factors to variation in flower and boll production (Sawan et al., 2002). Results in this table indicate that evaporation was the most important climatic factor affecting flower and boll production in Egyptian cotton. Sunshine duration is the second climatic factor of importance affecting production of flowers and bolls. Relative humidity and temperature at 1800 h were factors of lower contribution than evaporation and sunshine duration/day. Maximum temperature made a contribution less than the other affecting factors.

The highest contribution of evaporation to the variation in both flower and boll production (Sawan et al., 2002) can, however, be explained in the light of results as observed by Ward and Bunce (1986) in sunflower (*Helianthus annuus*). They stated that decreases of humidity at both leaf surfaces reduced photosynthetic rate of the entire leaf for plants grown under moderate temperature and medium light level. Kaur and Singh (1992) observed that in cotton flower number was decreased by water stress, particularly when applied at flowering. Seed cotton yield was about halved by water stress at flowering, slightly decreased by stress at boll formation, and not significantly affected by stress in the vegetative stage (6 to 7 weeks after sowing). Orgaz et al. (1992) in field experiments at Cordoba, SW Spain, grew cotton cultivars Acala SJ-C1, GC-510, Coker-310 and Jean cultivar 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 Jean cultivar 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-

Table 3: Selected factors and their relative contribution to variations of flower and boll production.

Selected climatic factors	Flower production * R.C. (%) First season	Second season	Combined data	Boll production R.C. (%) First season	Second season	Combined data
Maximum Temp [°C] (X_1)	–	5.92	–	–	5.03	–
Evaporation [mm d^{-1}] (X_4)	19.08	23.45	16.06	23.04	22.39	22.89
1800 h Temperature [°C] (X_6)	–	–	5.83	–	–	2.52
Sunshine [h d^{-1}] (X_7)	9.43	7.77	8.31	11.65	7.88	5.47
Maximum RH [%] (X_8)	8.46	–	–	–	–	–
Minimum RH [%] (X_9)	–	4.37	7.38	–	4.26	4.64
** R^2 % for selected factors	36.97	41.47	37.58	34.69	39.56	35.52
R^2 % for factors studied	40.22	45.03	40.73	38.43	42.87	37.90
R^2 % for factors deleted	3.25	3.56	3.15	3.74	3.31	2.38

* R.C. % = Relative contribution of each of the selected independent variables to variations of the dependent variable; ** R^2 % = Coefficient of determination in percentage form (Sawan et al., 2002).

season length and availability of irrigation water.

The negative relationship between sunshine duration and cotton production may be due to the fact that the species of *Gossypium* used is known to be a short day plant (Hearn and Constable, 1984) and as a result an increase of sunshine duration above that needed for cotton plant growth will decrease flower and boll production. Oosterhuis (1997) studied the reasons for low and variable cotton yields in Arkansas, with unusually high insect pressures and the development of the boll load during an exceptionally hot and dry August. Solutions to the problems are suggested, that is, 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 (Sawan, 2014, 2016).

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

Basic variables

The basic variables can be summarized as:

A) Dependant variables as earlier defined: (Y_1) and (Y_2) (Sawan et al., 2010).
B) Independent variables (Xs):

1) Irrigation on day 1 = 1. Otherwise, enter 0.0 (soil moisture status) (X_1);
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 to 6 (after flowering) (X_{11});
12) Lowest minimum relative humidity (minRH) [%] on days 3 to 6 (after flowering) (X_{12});
13) Largest maximum relative humidity (maxRH) [%] on days 7 to 12 (after flowering) (X_{13});
14) Lowest minimum relative humidity (minRH) [%] on days 7 to 12 (after flowering) (X_{14});
15) Lowest minimum relative humidity (minRH) [%] on days 50 to 52 (after flowering) (X_{15});
16) Daily light period (hour) (X_{16}).

Statistical analysis

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

Table 4: 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
(X_1) Irrigation on day 1	-0.1282	-0.0925
(X_2) Irrigation on day 0 or –1 (1st and 2nd day after irrigation)	-0.1644	-0.1403
(X_3) 1 is for the day prior to irrigation	-0.0891	-0.0897
(X_4) Number of days that temperature equaled or exceeded 37.5°C	0.1258	0.1525
(X_5) Range of temperature [°C] on day 1	-0.0270	-0.0205
(X_6) Broadest range of temperature [°C] over days 1 -12	0.0550	0.1788[d]
(X_7) Minimum RH [%] during day 1	0.1492	0.1167
(X_8) Maximum RH [%] during day 1	0.2087[c]	0.1531
(X_9) Minimum RH [%] during day 2	0.1079	0.1033
(X_{10}) Maximum RH [%] during day 2	0.1127	0.0455
(X_{11}) Largest maximum RH [%] on days 3-6	0.3905[a]	0.2819[b]
(X_{12}) Lowest minimum RH [%] on days 3-6	0.0646	0.0444
(X_{13}) Largest maximum RH [%] on days 7-12	0.4499[a]	0.3554[b]
(X_{14}) Lowest minimum RH [%] on days 7-12	0.3522[a]	0.1937[d]
(X_{15}) Lowest minimum RH [%] on days 50-52	-0.3440[a]	-0.4222[a]
(X_{16}) 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 (Sawan et al., 2010).

moisture status attaining a probability level of significance not exceeding 0.15 were deemed important (affecting the dependent variables) (Sawan et al., 2010), while 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 determinations (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).

Correlation estimates

Tables 4 to 6 show 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 (Sawan et al., 2010). 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 to 52 (after flowering). Flower and boll production were positively and highly correlated with the variables of largest maxRH (X_{11} and X_{13}) and lowest minRH (X_{14} and X_{15}) in the first season, minRH (X_7 and X_9), largest maxRH (X_{11}), and lowest minRH (X_{12}, X_{14} and 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 season. MaxRH was significantly correlated with the dependent variables in the first season, while the inverse pattern was true in the second season. 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 with the number of days during days 1 to 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 to 12 (X_6). The soil moisture status showed low and insignificant correlation with 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

Table 5: 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**
(X_1) Irrigation on day 1	-0.0536	-0.0467
(X_2) Irrigation on day 0 or –1	-0.1116	-0.1208
(X_3) 1 is for the day prior to the day of irrigation	-0.0929	-0.0927
(X_4) Number of days that temperature equaled or exceeded 37.5°C	-0.4192[a]	-0.3981[a]
(X_5) Range of temperature [°C] on day 1	-0.3779[a]	-0.3858[a]
(X_6) Broadest range of temperature [°C] over days 1-12	-0.3849[a]	-0.3841[a]
(X_7) Minimum RH [%] during day 1	0.4522[a]	0.4665[a]
(X_8) Maximum RH [%] during day 1	0.0083	0.0054
(X_9) Minimum RH [%] during day 2	0.4315[a]	0.4374[a]
(X_{10}) Maximum RH [%] during day 2	0.0605	0.0532
(X_{11}) Largest maximum RH [%] on days 3-6	0.2486[c]	0.2520[b]
(X_{12}) Lowest minimum RH [%] on days 3-6	0.5783[a]	0.5677[a]
(X_{13}) Largest maximum RH [%] on days 7-12	0.0617	0.0735
(X_{14}) Lowest minimum RH [%] on days 7-12	0.4887[a]	0.4691[a]
(X_{15}) Lowest minimum minRH [%] on days 50-52	-0.6246[a]	-0.6113[a]
(X_{16}) 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 (Sawan et al., 2010).

Table 6: 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**
(X_1) Irrigation on day 1	-0.0718	-0.0483
(X_2) Irrigation on day 0 or –1	-0.1214	-0.1108
(X_3) 1 is for the day prior to the day of irrigation	-0.0845	-0.0769
(X_4) Number of days that temperature equaled or exceeded 37.5 °C	-0.2234[b]	-0.1720[c]
(X_5) Range of temperature [°C] on day 1	-0.2551[a]	-0.2479[a]
(X_6) Broadest range of temperature [°C] over days 1-12	-0.2372[a]	-0.1958[b]
(X_7) Minimum RH [%] during day 1	0.3369[a]	0.3934[a]
(X_8) Maximum RH [%] during day 1	0.0032	-0.0911
(X_9) Minimum RH [%] during day 2	0.3147[a]	0.3815[a]
(X_{10}) Maximum RH[%] during day 2	-0.0094	-0.1113
(X_{11}) Largest maximum RH [%] on days 3-6	0.0606	-0.0663
(X12) Lowest minimum RH [%] on days 3-6	0.3849[a]	0.4347[a]
(X_{13}) Largest maximum RH [%] on days 7-12	-0.0169	-0.1442[d]
(X_{14}) Lowest minimum RH [%] on days 7-12	0.3891[a]	0.4219[a]
(X_{15}) Lowest minimum RH [%] on days 50-52	-0.3035[a]	-0.2359[a]
(X_{16}) 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 (Sawan et al, 2010).

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

Table 7: 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

(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) Min RH [%] during day 2; (X_{11}) Largest max RH [%] on days 3-6; (X_{12}) Lowest min RH [%] on days 3-6; (X_{13}) Largest max RH [%] on days 7-12; (X_{14}) Lowest min RH [%] on days 7-12; (X_{15}) Lowest minRH [%] on days 50-52; (X_{16}) Daily light period (hour). All entries significant at 1% level (Sawan et al., 2010).

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 the trend differed in the second season. These results indicated that relative humidity was the most effective and consistent climatic factor affecting boll production. The second most important climatic factor in our study was sunshine duration, which showed a significant negative relationship with boll production.

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 7). 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 to 6 (X_{11}), lowest minRH on days 3-6 (X_{12}), largest maxRH on days 7 to 12 (X_{13}), lowest minRH on days 7 to 12 (X_{14}) and lowest minRH on days 50 to 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 and X_{10}) were not included in the equations since they had very little effects on production of cotton flowers and bolls.

Relative humidity showed the highest contribution to the variation in both flower and boll production (Table 7). This finding can be explained in the light of results as observed by Ward and Bunce (1986) in sunflower (*H. annuus*). They stated that decreases of relative humidity on both leaf surfaces reduced photosynthetic rate of the whole leaf for plants grown under a moderate temperature and medium light level.

Reddy et al. (1993) found that cotton (*G hirsutum*) fruit retention decreased rapidly as the time of exposure to 40°C increased. Gutiérrez and López (2003) studied the effects of heat on the yield of cotton in Andalucia, Spain, from 1991 to 1998, and found that high temperatures were implicated in the reduction of unit production. There was also 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 to 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 from 0.53 to 0.72. These results are in line with the report of 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 was related to management practices, which coincide with the findings of 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 (Sawan, 2015).

Conclusions

Evaporation, sunshine duration, relative humidity, surface soil temperature at 1800 h, and maximum temperature were the most significant climatic factors affecting flower and boll production of Egyptian cotton. The negative correlation between each of evaporation and sunshine duration with flower and boll formation along with the positive correlation between minimum relative humidity value and flower and boll production, indicate that low evaporation rate, short period of sunshine duration and high value of minimum humidity would enhance flower and boll formation. It may be concluded that the 5-day accumulation of climatic data during the production stage, in the absence of sharp fluctuations in these factors, could be satisfactorily used to forecast adverse effects on cotton production and the application of appropriate production practices circumvent possible production shortage.

Finally, 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 proper management practices, such as, adequate irrigation regime and utilization of specific plant growth regulators could limit the negative effects of some climatic factors (Sawan, 2016).

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