

## A TEMPERATURE MODEL FOR COTTON PHENOLOGY

Reddy, K. R.  
Department of Agronomy Mississippi State University

Hodges, H. F.  
Department of Agronomy Mississippi State University

Mckinion, J. M.  
USDA-ARS Crop Simulation Research Unit Crop Science Research Laboratory

<https://hdl.handle.net/2324/8188>

---

出版情報 : BIOTRONICS. 22, pp.47-59, 1993-12. Biotron Institute, Kyushu University  
バージョン :  
権利関係 :

## A TEMPERATURE MODEL FOR COTTON PHENOLOGY

K. R. REDDY\*, H. F. HODGES\*, and J. M. MCKINION\*\*

\*Department of Agronomy, Mississippi State University, P O Box 9649, Mississippi State, MS, 39762

\*\*USDA-ARS, Crop Simulation Research Unit, Crop Science Research Laboratory,  
P O. Box 5367, Mississippi State, MS 39762

(Received June 15, 1993; Accepted Aug. 16, 1993)

REDDY K.R., HODGES H. F. and MCKINION J. M. *A temperature model for cotton phenology*. BIOTRONICS 22, 47-59,1993. Agricultural production is becoming more mechanized and based on improved technology, however, many important management applications depend on crop growth stage and growing status. Crop growth rate and developmental stage depends largely on weather conditions since planting and the crop responses to temperature. We conducted experiments in naturally lighted, temperature, carbon dioxide, water and nutrients controlled plant growth chambers. Upland cotton, *Gossypium hirsutum* L. and pima cotton, *G. barbadense* L. plants were grown at a range of temperatures from 20/12 to 40/32°C (day/night) in well watered and fertilized conditions. The plants were monitored daily to determine the rates of flower buds (squares) and flower formation, fruit maturation, and leaf/node formation. Also the duration of leaf and internode expansion was determined. Modern cultivars of these two cotton species develop squares faster at the same temperatures than cultivars used two or three decades earlier. Temperature responses of both species for time to first square, squaring to flowering, mainstem and fruiting branch node formation, and duration of leaf and internode Expansion were nonlinear. A quadratic formula expressing the duration of various developmental stages as functions of average temperature fit the data better than linear equations. Pima cotton square and fruit formation were more sensitive to temperature than upland cotton cultivars. At average temperatures above 27°C pima cotton developed squares more slowly than upland cotton. The lengths of square and boll maturation periods in both cotton species were directly related to the temperature to which they were exposed. However, pima cotton took more time for these developmental phases compared to upland cotton. The ratio of mainstem nodes formed per fruiting branch node formed was temperature sensitive and nonlinear. Data on these developmental events/processes were used to estimate timing of leaf unfolding, duration of leaf and internode expansion, and several reproductive processes as functions of temperature.

**Key Words:** Cotton, *Gossypium hirsutum* L., *G. barbadense* L., flowering, leaf and stem development, phenology, modeling.

## INTRODUCTION

Temperature plays a dominant role in controlling growth and developmental rates of plants. There are major differences among plant species in their sensitivities to temperature. Even cultivars or ecotypes within a species vary in their sensitivity to temperature. Any particular genotype has unique temperature optimum, and above- and below-optimum temperature response curves. The mechanisms and sensitivities of the mechanisms to environmental stimuli controlling developmental events vary among cultivars. Photoperiod is an important environmental cue in some species, but is not important in modern commercial cotton cultivars (3). The environmental regulation of time required for flower bud formation, the intervals between leaves, and flowers, the time required for fruit maturation, and the interrelationships among them form much of the essential pattern controlling the morphogenetic development unique to each species or cultivars.

Hesketh and Low (5), Moraghan et al. (11), and Hesketh et al. (4) reported cotton developmental rates at different temperatures. Baker et al. (2) used their data in developing a computer-based cotton growth and development model for simulating field-grown cotton. This model predicted first square about 20% later than in field conditions. In addition, 30% more time was predicted by the model for time intervals between mainstem nodes than was observed for non-stressed field grown cotton. They also found that the time intervals between fruiting branch nodes were 50% greater than was observed in field conditions. They calibrated their model to simulate the field-grown crop data by introducing multiplying factors into the various temperature-response equations (2).

The varieties for which that temperature response information is available are no longer used commercially and many of the modern cultivars are earlier in maturity (16). In addition, modern cultivars partition more dry matter into reproductive organs and behave in a more determinate plant habit than do old cultivars. Many cultivars used today require less time to reach first square, flower, or open boll than older varieties. They also require less time between developmental events and stop vegetative development earlier than older cultivars, but specific phenological responses to temperature are largely not known. The objectives of this study were to (1) determine temperature effects on phenological responses of modern upland and pima cotton cultivars, and (2) develop phenological models for predicting various developmental phases, expansion duration of leaves and internodes, and time intervals between leaves on the mainstem and fruiting branches. Simulation models, once developed based on data collected at a wide range of temperatures, can be used to predict developmental events over a wide range of environmental conditions. Knowing the timings of various developmental events of a crop allows planning of production management practices and the application of improved technology.

**MATERIALS AND METHODS***Collection of Database :*

Closed environmental growth chambers located outside were used in this study. These growth chambers are known as Soil-Plant-Atmosphere-Research (SPAR) units (1, 12, 13, 14, 15) and are located at Mississippi State University, Mississippi, USA. These units have the ability to control air temperature, water, nutrients, and atmospheric CO<sub>2</sub> concentration.

Each SPAR unit consists of a steel bin containing a rooting medium (1 m high × 2 m long × 0.5 m wide), a plexiglass chamber (2.5 m high × 2 m long × 1.5 m wide), to accommodate the aerial plant parts, a heating and cooling system, and a monitoring and control system. Variable-density shade cloths around the edges of the cotton canopies were adjusted regularly to plant heights in each cabinet to simulate the presence of other plants and to eliminate the need for border plants. Conditioned air was introduced at the top of the plexiglass chamber and circulated through the plant canopy with sufficient speed to cause leaf flutter and minimize boundary layer resistance. The air was returned to ducts just above the soil surface.

Chilled ethylene glycol was supplied to the cooling system via several solenoid valves that opened and closed depending on the temperature requirement. Electrical-resistance heat was provided in short pulses as needed to fine tune the air temperature. After emergence, carbon dioxide was maintained within  $\pm 10 \mu\text{l l}^{-1}$  of set points during the daylight hours.

Throughout the growing period, environmental data were collected at 10-s intervals and summarized over 900-s periods. Air temperatures were maintained  $\pm 0.5^\circ\text{C}$  of the set points 95% of the time. The average daily temperature was calculated from emergence to the date of first square, or the average daily temperature during a developmental event. Data directly measured included dry bulb temperatures, dew point temperatures, solar radiation, and photosynthetically active radiation. The plants were watered automatically with Hoagland's nutrient solution so that water or nutrients were not limiting (7). Observations were taken on the same 9 plants in each chamber daily to determine times of the different events.

The results presented here are from several experiments conducted during the summers of 1989 to 1992 and generally of two types (12, 13, 15). One type was conducted by planting seeds of upland cotton (*Gossypium hirsutum* L.) cv. DES 119, DPL 5415, DPL 50, and pima cotton (*G. barbadense* L.) cv. S-6 into SPAR units. The temperature in the SPAR units was maintained at 28/24°C (day/night) for a few days to allow seedling establishment, and then temperature treatments were imposed. Temperature treatments included 20/12, 25/17, 30/22, 35/27, 40/32°C (day/night). The daytime temperatures were initiated one hour after sunrise and returned to night conditions one hour after sunset.

A second type of experiment was conducted by planting seeds in 12 L pots containing a sand: vermiculite mixture (3:1 by volume) grown in nursery

under optimal water and nutrient conditions, and moved into the SPAR units at flowering. The plants were arranged in rows with nine plants  $m^{-2}$  in the SPAR units. Experiments of this type were conducted to determine the period from flowering to open boll.

Days from emergence to the appearance of the first square, 3 mm in length, were recorded on nine plants at each temperature. Cotton flowers are creamy-white (delta or upland) or yellow (pima) the day of anthesis, and become purple by the day after anthesis. This allows one to tag each flower with the date of anthesis and subsequently the date of open boll was identified when cotton lint could first be seen through cracks between the carpels. The rate of node formation was the time interval required from the day a leaf unfolded until the next leaf unfolded on either the mainstem or fruiting branch. Leaf expansion duration data was obtained by measuring the leaf length daily from the day of leaf unfolding until the leaf did not expand on succeeding days. When there were no differences between varieties and species, all the data were used to develop a common equation for both the species.

#### *Data Analysis:*

Various models such as linear, quadratic, power and exponential responses were fitted for the data of daily development of various phases or events on average temperature. A quadratic formula, expressing the duration of various developmental phases of unlike events (emergence to squaring, square maturation period, and boll maturation period), duration of various like events (adding successive nodes on the mainstem or branches), and expansion duration of leaves and internodes as a function of average temperature was found to be most appropriate. Thus the method of model construction considered daily rate of development ( $\Delta D$ ) as a function of temperature; viz.

$$\Delta D = a + bT + cT^2$$

where  $T$  represents the average daily temperature and  $a$ ,  $b$ , and  $c$  are constants. With the summation of all the elementary developments  $\Delta D$  for the completion of a developmental phase or for the completion of duration expansion of organs, the total value is equal to 1 (completion of stage commencing day 1 and ending  $m$ ). That is

$$\sum_{i=1}^m \Delta D = 1$$

Parameters and coefficients of correlation of the quadratic fit to the data are presented in Table 1 for various phenological events of upland and pima cotton cultivars.

## RESULTS AND DISCUSSION

#### *Reproductive Initiation:*

Floral initiation, defined by time between emergence to the appearance of

Table 1. Parameters for quadratic equations regressing daily developmental rate ( $y$ ) for various phenological events as a function of average daily temperature ( $x$ ) and correlation coefficients.

$(y = a + bx + cx^2)$				
	a	b	c	$r^2$
<b><i>Daily developmental rate for emergence to square</i></b>				
Upland	-0.12645387	0.01142172	-0.00019488	0.98
Pima	-0.15931218	0.0147265	-0.00027485	0.99
<b><i>Daily developmental rate for square maturation period</i></b>				
Upland	-0.11482641	0.00967002	-0.00014318	0.94
Pima	-0.06095668	0.00618709	-0.00009917	0.94
<b><i>Daily developmental rate for boll maturation period</i></b>				
Upland	-0.02609603	0.00215915	-0.00001528	0.99
Pima	-0.01862659	0.00180252	-0.00001368	0.99
<b><i>Daily developmental rates for mainstem fruiting nodes</i></b>				
Upland or Pima	-0.74138299	0.06221284	-0.00076398	0.97
<b><i>Daily developmental rates for fruiting branch nodes</i></b>				
Upland or Pima	-0.40870514	0.03728445	-0.00057852	0.93
<b><i>Daily developmental rate for expansion duration of internodes</i></b>				
Pima	-0.031268	0.0066294	-0.0000936	0.99
<b><i>Daily developmental rate for expansion duration of leaves</i></b>				
Pima	-0.059751	0.00806128	-0.0001310	0.97

a square of 3 mm in length, was not affected by enriching the atmosphere with CO<sub>2</sub>, and thus data from different CO<sub>2</sub> treatments were used in fitting quadratic regressions and parameters along with correlation coefficients are presented in Table 1. The reciprocals of time from emergence to the appearance of first square as a function of average growing temperature for both cotton species were very similar at 27°C and below (Fig. 1). At temperatures above 27°C, the upland cotton slowly decreased its rate of progress toward forming first square. Both species appeared to stop progress towards developing first square as temperature decreased to 15°C.

About 40 d were required at 20°C and only 23 d at 30°C to reach first square for upland cotton cultivars. The data from Moraghan et al. (11), when treated in the same manner, predicted 56 d at 20°C and 43 d at 30°C for upland cotton, cv. M-8. Hesketh et al. (4) reported 57 d at 20°C and 35 d at 30°C for another upland cultivar. Baker et al. (2) developed a cotton model, GOSSYM, that simulated this phenological response based on the temperature-response data of Moraghan et al. (11). When this model was first tested, they found that the model predicted 20% more time to reach first square than was observed in field conditions. They calibrated their model by introducing

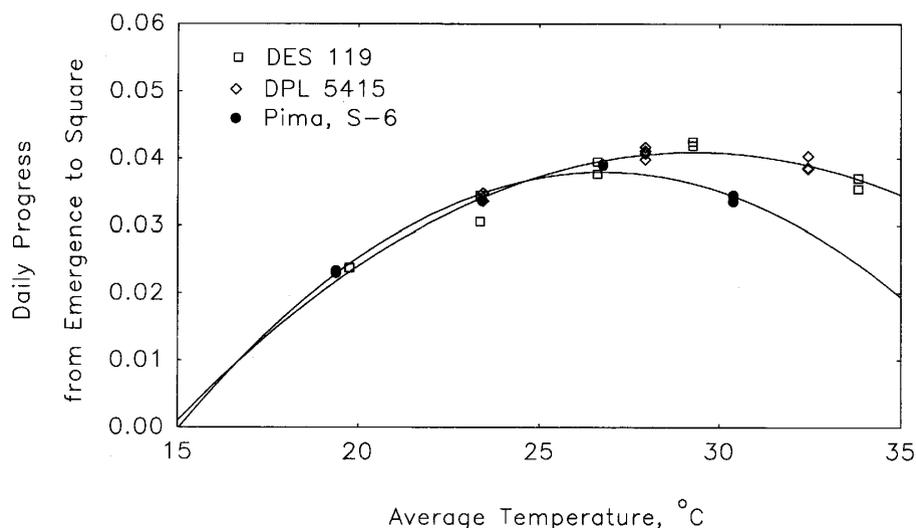


Fig. 1. Quadratic relation between average temperature and the daily developmental rate from emergence to floral initiation for upland and pima cotton cultivars. Floral initiation was defined as time required from emergence to first flower bud or square of 3 mm in length. The appropriate regression equations and regression coefficients along with correlation coefficients for the fitted curves are presented in Table 1.

multipliers into the temperature response data for this phenological event. This adjustment improved the predictions at near-optimum temperature, but predicted rates were too fast at both below- and above-optimum temperatures. New pima cotton decreased its rate of progress toward first square more than upland cotton at temperatures above 27°C, suggesting that it was more sensitive to high temperature than upland cotton (Fig. 1). The pima cotton was more sensitive to high temperatures, requiring more time to produce a square at 30°C than the upland cotton cultivars, and the equations projected even greater differences as temperature increased (Fig. 1 and Table 1). Moraghan et al. (11) reported that times to first square for pima, cv. S-2, were 49 d at 20°C and 32 d at 25°C, and this then increased to 45 d at 30°C suggesting injury at higher temperatures. The differences between our results and the earlier published work are due to several reasons. One is cultivars (16), and another is probably the environments from which the developmental rates in the earlier work were determined. The data presented here suggest that modern cultivars of both the species of cotton initiate squares much earlier than those grown several years ago, and modern cultivars respond to temperature differently than the cultivars released two to three decades ago due to improvements in their ability to produce squares or fruiting structures at higher temperatures. Such data are needed to improve the predictive capabilities for crop management and yield forecasting models.

Others have used growing degree days as a way of summarizing temperature data to predict time of first square (9). This procedure has been only moderately successful because of the variability in plant responses, but

maybe satisfactory if above optimum and low temperature thresholds are adequately considered in developing the relationships. The reason for variability in numbers of heat units required to reach first square in different weather conditions is apparent from this data. The response curves are not linear, so progress toward squaring is not the same at all temperatures.

#### *Square Maturation Period:*

The reciprocals of square maturation period (one over number of days to progress from square to open flower) was plotted against temperature (Fig. 2) and coefficients are presented in Table 1 for both species of cotton. Daily progress of square maturation period for upland cotton cultivars increased as temperature increased at the low end of the temperature range: however the developmental rate at temperatures above 27°C did not appear greater than development at 27°C. Developmental progress equations also projected to zero development from squaring to flower at about 14°C (Table 1 and Fig. 2). Our results on rates of progress from square to flower formation were similar to those reported by Hesketh and Low (5) and Hesketh et al. (4), except at low temperature where they had only limited data. Apparently changes in varieties have not influenced the sensitivity of cotton to temperature during the square maturation period.

Daily progress of pima cotton toward flower formation reached zero at about 12°C. The developmental progress of pima cotton from square formation to flower was less sensitive to below optimum temperature than upland cotton, and pima progressed even less rapidly at optimum temperatures and above than upland cotton. The upland cotton cultivars progressed from squares to flowers about 25% more rapidly at 27°C than pima cotton, cv. S-6. About 46

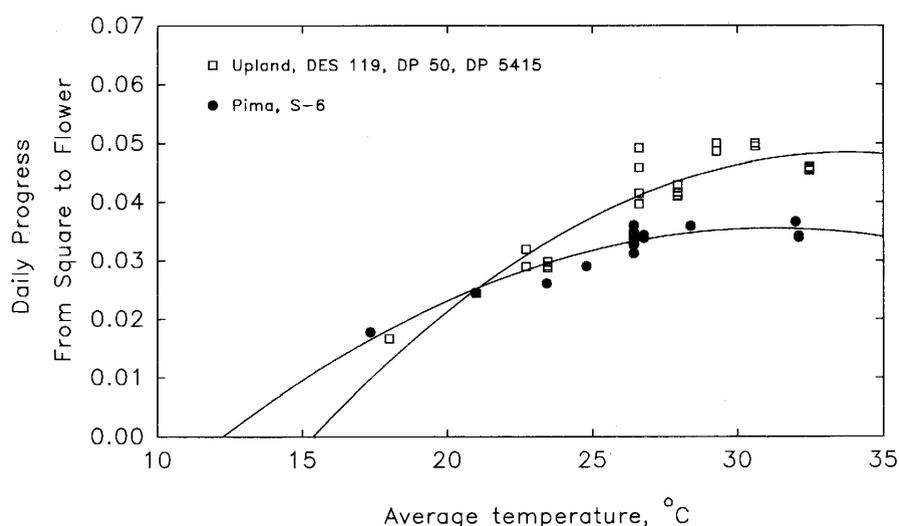


Fig. 2. Influence of temperature on daily developmental rate from square (3 mm in length) to open flower for upland and pima cotton cultivars. The appropriate regression equations and regression coefficients along with correlation coefficients for the fitted curves are presented in Table 1.

d were required at 20°C to develop flowers after squares were visible, but only 21 or 28 d at 30°C for upland and Pima cotton cultivars, respectively.

*Boll Maturation Period and Boll Size :*

The time required from flower production to mature boll is also very temperature dependent. The reciprocal of days required to produce an open boll at different temperatures was nearly linear throughout the temperature range tested (Table 1). The differences between pima and upland cotton cultivars for boll maturation period was about 2 to 6 d over the temperature range tested (Fig. 3). Progress toward open bolls was only about one-half the rate at 20°C as at 30°C. About 40 d were required from anthesis to open boll at 30°C. Boll maturation period of these upland cotton cultivars was faster at low temperatures and slower at high temperatures than those reported by Hesketh and Low (5).

We did not see a decline in rate of boll development at temperatures above 27°C as was observed for rates of square formation; however we did observe lower boll weights, data not shown, for bolls produced at higher temperatures. Pima boll size was particularly sensitive to temperature. Maximum boll weight was attained at 26°C with only 88% and 44% as much dry matter produced per boll when plants were grown at 20°C and 32°C, respectively. Upland cotton averaged 6.0 g per boll on plants grown at 26°C, but bolls weighted 10% less on plants grown at 20°C and 32°C. Clearly, the pima cotton boll size was much more sensitive to temperature than upland cotton boll weight.

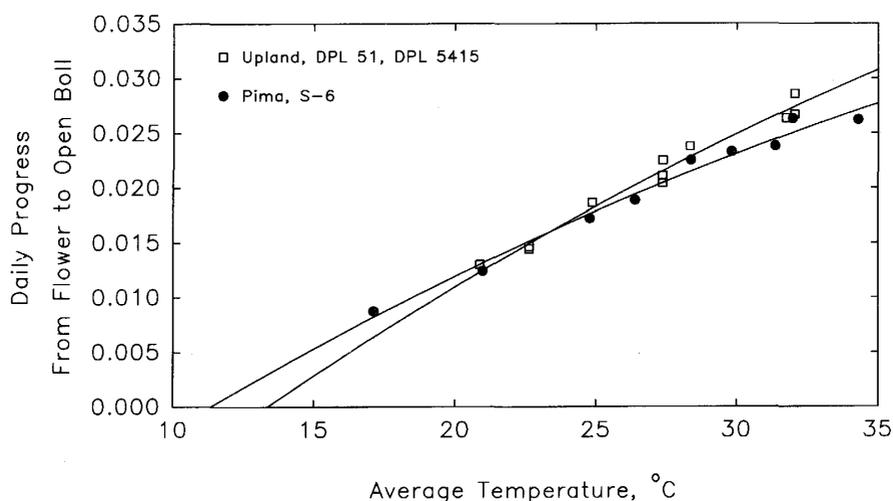


Fig. 3. Relation between reciprocal of boll maturation period (one over days from open flower to open boll) and average daily temperature for upland and pima cotton cultivars. The appropriate regression equations and regression coefficients along with correlation coefficients for the fitted curves are presented in Table 1.

*Mainstem and Fruiting Branches Nodes :*

Development of mainstem and fruiting-branch nodes is an important aspect of cotton crop development; because these determine the number of leaves produced and thus canopy development and light interception. In these experiments, rates of node formation were not different between upland and pima cotton cultivars so the data from both the species of cotton were used to develop quadratic equations (Fig. 4 and Table 1). These data show the reciprocal of days required to produce a node above the first fruiting branch on the mainstem and the reciprocal of days required to produce nodes on the fruiting branches themselves. Mainstem nodes above the first fruiting branch were produced at progressively faster rates as temperature increased to 37°C (Fig. 4). The rate of mainstem node addition increased more than rates of fruiting branch nodes increased as temperature increased. More rapid production of mainstem leaves/nodes at warmer temperatures compared to the production of fruiting branch leaves/nodes results in a changing ratio of mainstem to fruiting branch leaves, depending on the temperature. Thus, growing temperature alters the architectural form of the plant. Studies in which phenology of cotton is being predicted by even simple temperature models (9) need detailed organ developmental-temperature functions to accurately predict plant development and growth relationships. Progress toward the next node of both mainstem and fruiting branches decreased to zero as temperature decreased to 14.5°C.

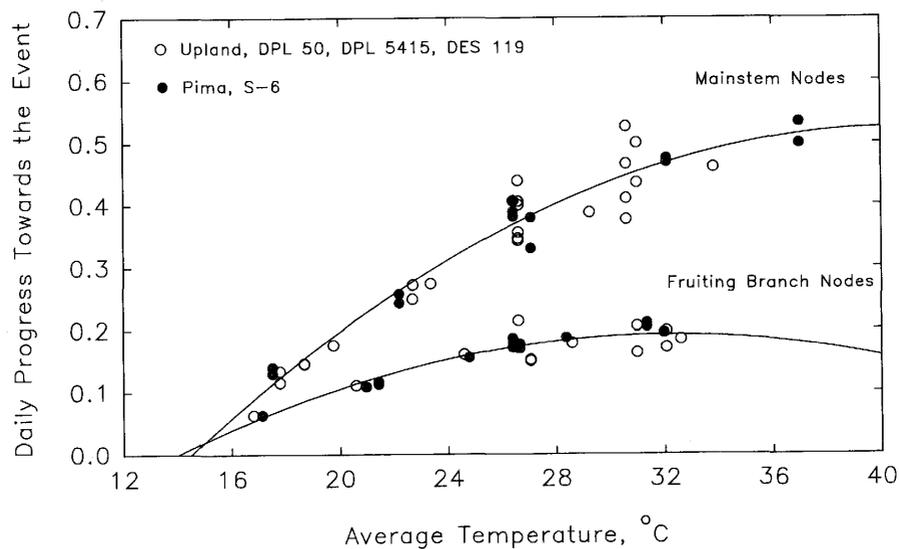


Fig. 4. Effect of average daily temperature on the daily development of nodes on the mainstem and fruiting branches for upland and pima cotton cultivars. We found that time intervals between successive squares, flowers and leaf unfolding intervals as defined by appearance of three main veins visible from the upper side of the leaf are not different. The appropriate regression equations and regression coefficients along with correlation coefficients for the fitted curves are presented in Table 1.

The number of days required to produce an additional mainstem node above the first fruiting branch was very stable at near-optimum temperature (Fig. 5). The first fruiting branch was produced at the sixth mainstem node. Only two to three days were required to produce any main stem node in positions 6 to 17. There were no significant differences in time required to produce mainstem nodes due to atmospheric  $\text{CO}_2$  concentrations suggesting that carbon supply was not limiting vegetative development during this period.

The time required to produce mainstem nodes prior to the first fruiting branch node was considerably longer than that required after a fruiting branch was produced. The reasons cotton plants require longer to produce pre-fruiting mainstem branch nodes are not clear. The time required became progressively less as more prefruiting nodes were developed. We know that during early development a considerable fraction of the total dry matter produced was partitioned to root growth (8). One could argue that such a genetically-controlled partitioning coefficient early in the life of the plant might leave only limited energy available for shoot growth and thus delay leaf development. However, if leaf development was delayed due to insufficient carbohydrates, then growing the plants in high  $\text{CO}_2$  environments should alleviate the carbohydrate shortage and allow more "normal" leaf developmental rates. That did not occur in either of our high  $\text{CO}_2$  environments, so the reason for slower leaf development at the pre-fruiting nodes is still unexplained. Such a phenomenon was observed in fruiting cotton plants (12, 13). In that case node additions reflected intra-plant competition with the plant's propensity to bear fruit. Another unexplained phenomenon in this data-set is the rate of leaf/node development at node two.

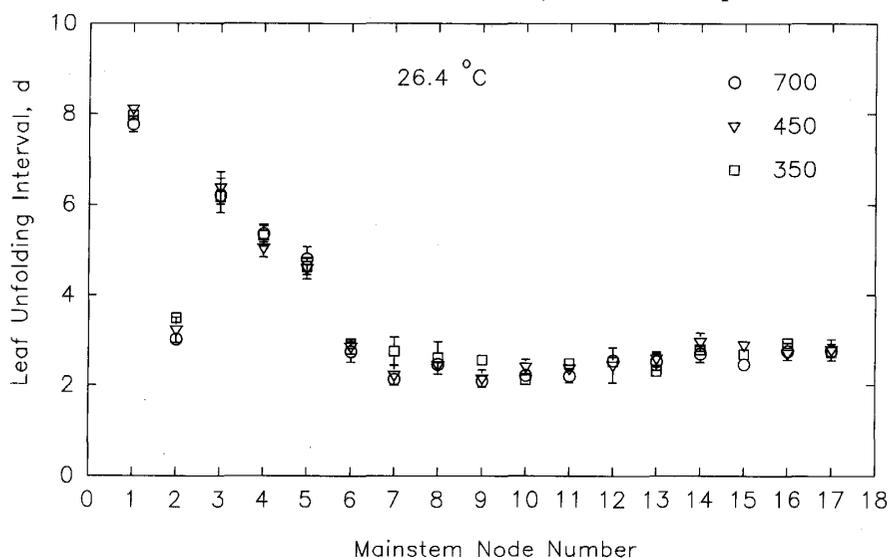


Fig. 5. Time required for leaf unfolding on mainstems of pima cotton, cv. S-6 grown at an average temperature of 26.4°C and in 350, 450 and 700  $\mu\text{L L}^{-1}$   $\text{CO}_2$  concentrations.

In all environmental treatments the time required to produce node two was only about 3 days; whereas it required about eight and six days to produce nodes one and three, respectively. That result has occurred repeatedly in different experiments involving different varieties and growing conditions.

*Expansion Duration of Leaf and Internode:*

The time required for a mainstem leaf to expand decreased gradually as temperature increased to about 30°C. The daily progress of leaf and internode expansion duration is plotted against temperature in Fig. 6. The equation (Table 1) fit the data with a correlation coefficient of 0.99. Leaf petiole expansion occurs simultaneously with the lamina expansion (data not shown). About 21 days were required for leaves to fully expand at 20°C and only 15 days at 30°C; whereas internodes required about 16 days to expand at 20°C and only 12 d at 30°C. The internode below the node to which a leaf is attached begins expanding two days after the leaf unfolds. There is limited information available on the growth responses of individual organs to temperature. Expansion duration and rates of expansion of cotton leaves and internodes were not available for the models of Baker et al. (2), Jackson (9) and Kiniry et al. (10). Leaf expansion duration at a particular temperature was similar regardless of the leaf position on the mainstem (14).

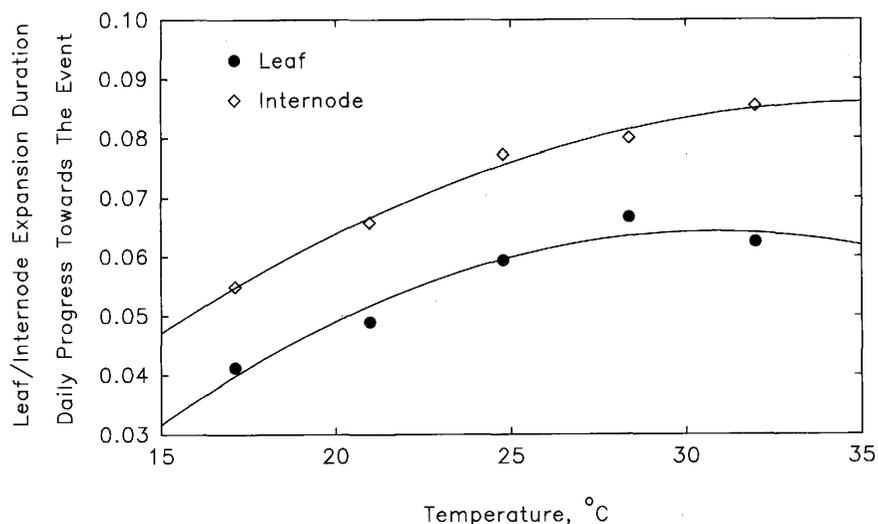


Fig. 6. Daily expansion duration of leaf and internode as influenced by temperature for upland and pima cotton cultivars. The appropriate regression equations and regression coefficients along with correlation coefficients for the fitted curves are presented in Table 1.

### SUMMARY AND CONCLUSIONS

A detailed analysis of temperature effects on adding leaves/squares/flowers on the mainstem and fruiting branches of upland and pima cotton is

presented. Also the time intervals for various reproductive phases such as the time from emergence to first square, square maturation period, and boll maturation period along with the duration of leaf and internode expansion are presented. The daily rate of development concept was used to fit models for temperature. Cotton's phenological developmental rate response to temperature deviated considerably from a linear relation. Developmental rate and duration of internode and leaf expansion responded to temperature in a quadratic manner. Data such as these are essential for modeling the organogenesis of plants and will be useful to general plant maps for both cotton species under optimal water and nutrient conditions. Nutrient- and water-deficit effects must be added to account for developmental events in stress environments.

Time to first square was more sensitive to temperatures above 27°C than other developmental events, and pima cotton was delayed considerably more than upland cotton to above optimum temperatures. Major differences between recently developed cultivars and those of two or three decades earlier were due to time to produce first square. The time to first square became greater in pima cotton at temperatures above 27°C, but the time required to progress from squaring to flowering remained constant from 26°C to 34°C. Boll-filling period became shorter as temperatures increased, and boll size was reduced at temperatures above or below 26°C. Fruiting branch node additions were only mildly sensitive to temperature in the temperature range where cotton is typically grown, but mainstem node addition rates were about twice as fast at 30°C as at 20°C. Pima and upland cotton plants added mainstem fruiting and fruiting-branch nodes about equally when grown at similar temperature. The effect of CO<sub>2</sub> on leaf unfolding intervals was not significant suggesting that carbon supply was not limiting vegetative developmental rate. A longer period was required for prefruiting mainstem nodes to be developed than for fruiting nodes, and it required more time for the early prefruiting nodes to develop than for the latter ones. The time during which a leaf or internode expended was only about 75% as long at 30°C as at 20°C, and internodes required only about 75% as much time to expand as leaves. The above information is being used in crop model development. The model allows prediction of canopy development and light interception as well as a number of other plant processes. It provides information that is useful in the timing of several agricultural production technologies being used.

#### ACKNOWLEDGEMENTS

The capable technical assistance of Sam Turner, Wendell Ladner, Raymond Smithey and Kimber Gourley is gratefully recognized. This research was supported in part by USDA-ARS, NRICGP Agreement Number 91-37100-6626.

## REFERENCES

1. Acock B., Reddy V. R., Hodges H. F., Baker D. N. and McKinion, J. M. (1985) Photosynthetic response of soybean canopies to full-season carbon dioxide enrichment. *Agron. J.* **77**, 942-947.
2. Baker D. N., Lambert J. R. and McKinion J. M. (1983) GOSSYM: A simulator of cotton crop growth and yield. *South Carolina Experimental Station Technical Bulletin*. 1089.
3. Ephrath J. E. and Hesketh J. D. (1991) The thermal-photoperiod requirement for floral bud growth. *Biotronics* **20**, 1-7.
4. Hesketh J. D., Baker D. N. and Duncan W. G. (1972) Simulation of growth and yield in cotton. II. Environmental control of morphogenesis. *Crop Sci.* **12**, 436-439.
5. Hesketh J. D. and Low A. (1968) Effect of temperature on components of yield and fibre quality of cotton varieties of diverse origin. *Cotton Grower Review* **45**, 243-257.
6. Hesketh J. D. and Warrington I. J. (1989) Corn growth response to temperature: rate and duration of leaf emergence. *Agron. J.* **81**, 696-701.
7. Hewitt E. J. (1952) Sand and water culture methods used in the study of plant nutrition. Pages 189. *Technical Communication* no. 22. Commonwealth Bureau of Agriculture and Plantation Crops, East Mailing, Maidstone, Kent, Commonwealth Agricultural Bureaux, Farnham Royal, Bucks, England.
8. Hodges H. F., Reddy K. R., McKinion J. M. and Reddy V. R. (1993) Temperature effects on cotton. *Mississippi Agricultural and Forestry Experiment Station Bulletin*. 990.
9. Jackson B. S. (1991) Simulating yield development using cotton model COTTAM. Pages 171-180 in: Hodges T (ed.) *Predicting Crop Phenology*. CRC Press, Boca Raton, Florida.
10. Kiniry J. R., Rosenthal W. D., Jackson B. S. and Hoogenboom G. (1991) Predicting leaf development of crop plants. Pages 29-42, in: Hodges T (ed.) *Predicting Crop Phenology*. CRC Press, Boca Raton, Florida.
11. Moraghan B., Hesketh J. D. and Low A. (1968) The effects of temperature and Photoperiod on earliness of floral initiation among strains of cotton. *Cotton Grower Review* **45**, 91-100.
12. Reddy K. R., Reddy V. R. and Hodges H. F. (1992a) Temperature effects on early season cotton growth and development. *Agron. J.* **84**, 229-237.
13. Reddy K. R., Hodges H. F., McKinion J. M. and Wall G. W. (1992b) Temperature effects on Pima cotton growth and development. *Agron. J.* **84**, 237-243.
14. Reddy K. R., Hodges H. F., and McKinion J. M. (1993) Temperature effects on Pima cotton leaf growth. *Agron. J.* **85**, 681-686.
15. Reddy V. R., Baker D. N. and Hodges H. F. (1991) Temperature effects on cotton canopy growth, photosynthesis, and respiration. *Agron. J.* **83**, 699-704.
16. Wells R. and Meredith W. R. (1984) Comparative growth of obsolete and modern cotton cultivars. III. Relationship of yield to observed growth characteristics. *Crop Sci.* **24**, 868-872.