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Thermal environment of cotton irrigated using canopy temperature

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Abstract. The threshold canopy temperature method for controlling a drip irrigation system includes a physiologically based threshold temperature and irrigation application rate that responds to the environment. Energy input from the environment causes canopy temperature to exceed the threshold value and irrigation is then applied. This study evaluated temperature distributions, amount of optimum time, and the amount of irrigation control time for cotton where irrigation scheduling was controlled by different threshold temperatures during the years 1988 to 1991. Optimum time for cotton growth was defined as the accumulated time that canopy temperatures were between 25 and 31 °C and the time accumulated above different threshold temperatures was designated as irrigation control time. Threshold temperatures over a 26 to 32 °C range altered the frequency distribution of temperature within the optimum temperature range (25–31 °C) by reducing temperatures above the threshold. Frequency of canopy temperatures of a 28 °C threshold temperature treatment decreased in the 28 to 29 °C increment and then remained below air temperature. Irrigation control time was more sensitive than optimum time to changes in threshold temperature between 26 and 31 °C. Optimum time and irrigation control time of the 28 °C threshold temperature varied by 37% and 29%, respectively. Lint yields in 1988 and 1990 were high while those in 1989 and 1991 were low because of unfavorable weather. Irrigation amounts applied during DOY 198-273 that were above 20 cm in high yield years or 12 cm in low yield years did not increase yield.

Temperature significantly influences plant vegetative growth and phenological development. The metabolism of plants is affected by temperature in such a manner that there is an optimal thermal range for their growth and development (Burke et al. 1988). The existence of an optimal thermal range implies that some plant temperatures are more conducive to plant growth than others and that an increase in the amount of time that the plant is within the optimal range will result in increased plant growth.

Continuous measurement of canopy temperature and application of irrigation for 15-minute periods when a threshold temperature was exceeded has been demonstrated as an automated irrigation scheduling procedure for cotton using a drip irrigation system (Wanjura et al. 1992). Plant temperature is influenced by its water status (Idso et al. 1982; Grimes et al. 1987) which can be altered through irrigation. Two assumptions that are made in using canopy temperature for irrigation management are that, first, canopy temperatures above the threshold indicate inadequate plant water status and second plant growth or productivity are positively correlated with the amount of time that the plant's temperature is within its optimal thermal range.

Optimum time for crop production is a concept that recognizes there is a specific temperature where growth is maximized. A field grown crop does not grow under a constant temperature regime but rather in a fluctuating thermal environment. Burke et al. 1988 defined the thermal kinetic window for cotton as 23.5–32 °C. Earlier research by Arndt (1945) found that the optimum temperature for cotton growth was 27 °C after germinating for three days. An analysis of the thermal dependence of reaction velocity of the enzyme glutathione reductase from cotton showed that velocity was highest at 28 °C. In this paper an optimal thermal range of 25–31 °C was selected where reaction velocity is predicted to be within 33% of its maximum value. Thus the *optimum time* (OPT) for cotton is the time that the canopy temperature is within a range from 25–31 °C, Fig. 1. Mathematically, OPT = Σ time, when $31\,°C < T_c > 25\,°C$. Optimum time can be determined from measured canopy temperatures or specified by values of environmental factors that allow the plant canopy to maintain its optimal thermal range. Since plant canopy temperature depends on both the atmospheric environment and the water status of the plant, a well-watered plant was used as a reference.

In temperature-controlled-irrigation scheduling (TCIS) using a drip irrigation system the threshold temperature

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determines when and how much water is applied. The cumulative time that the threshold temperature is exceeded represents the maximum available time for irrigation and is termed *irrigation control time* (ICT), Fig. 1. Expressed mathematically as ICT = Σ time, when $T_c > T_t$, where T_c is canopy temperature and T_t is the threshold canopy temperature level. Irrigation control time depends on the threshold canopy temperature level and the environment. The overall result is that the threshold temperature level determines irrigation control time which controls the amount of water applied. Applied water affects the range and distribution of canopy temperature.

The TCIS method assumes that plant canopy temperature is a sufficient indicator of plant water stress, see Fig. 1. Canopy temperature is a direct indicator of crop water status and atmospheric energy dynamics. Canopy temperature is used to control irrigation by automatically applying irrigation through a drip system whenever a threshold canopy temperature is exceeded. The use of TCIS requires that the energy input from the environment be large enough to raise the crop canopy temperature above the threshold temperature.

In order to assess the effect of canopy temperature changes that result from TCIS, an estimate of the maximum amount of time that the canopy temperature could be within a specific thermal range is required. Drip irrigated cotton where water application was controlled by a threshold temperature of 28 °C produced the highest average yield during a four-year study (Wanjura et al. 1992). The thermal environment of cotton where irrigation was controlled by a 28 °C threshold is used as a reference because yield was maximum and presumably water status was optimized. The primary motivation for analyzing the thermal environment of the canopy is to determine whether the accumulation of temperature above a threshold limits the use of threshold canopy temperature to control irrigation scheduling.

The purpose of this paper is to examine the temperature environment of drip irrigated cotton where scheduling was controlled by threshold temperature. The specific objective was to evaluate temperature distributions, amount of time within the optimum temperature range, and irrigation control time.

Materials and methods

The analysis was conducted using data from a cotton production area where irrigation supplements rainfall and the length of the growing season is often limited by low temperature. The period of the growing season that was used in the analysis was the middle portion of the crop production cycle (DOY 198–273) when fruit are initiated and matured, and most irrigation is applied. Plant canopies were the maximum size during this period which was optimum for measuring canopy temperature with infrared thermometers.

The data was collected from TCIS studies conducted on the Texas Agricultural Experiment Station located at Lubbock, Texas between 1988–1991. The experimental plots were flat-broken with a moldboard plow each year prior to planting and herbicide broadcast and incorporated. Fertilizer application, based on soil samples, was applied before planting. A preplant furrow irrigation was applied when needed to ensure adequate moisture for seed germination and to refill the top 2 m of soil to field capacity.

Cotton was planted in rows oriented east-west spaced 0.76 m (30 inches) apart. Plot size was 18 rows wide by 30.5 m long. Temik [1] was applied in the seed furrow at planting for the control of thrips. Irrigation was applied through 16 mm diameter polyethylene dripline emitter hose with 61 cm spacing between emitters. The dripline hose was placed on the soil surface in each row. Nitrogen was applied to the plots through the irrigation system at the rate of 0.221 kg(N)/ha-mm.

All plots were instrumented as follows: Infrared thermometers (IRTs) were placed on each side of a row to view the upper one-third of the canopy, and net radiation was measured above the canopy. One anemometer and pyranometer were positioned 2 m above the

[1] The use of trade names does not imply endorsement by the U.S. Department of Agriculture

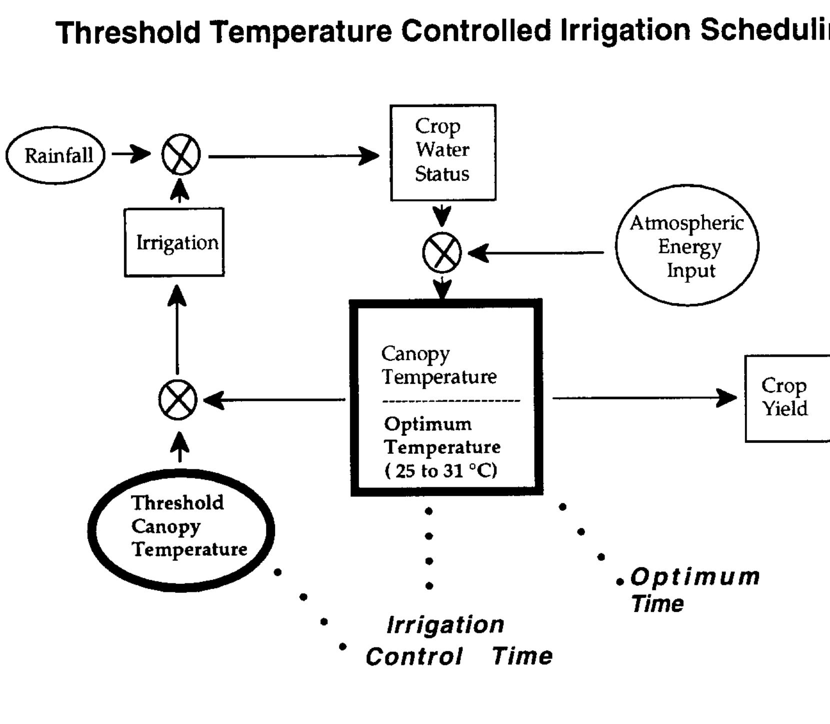

Fig. 1. Representation of threshold temperature controlled irrigation scheduling which depicts the relationship of optimum time and irrigation control time with specific parameters

soil surface in a well-watered treatment to measure ambient conditions. Dry bulb air temperature (AT) and wet bulb air temperature were also measured at a 2 m height in the study area. Instruments were located in the north-east quadrant of each plot to provide maximum fetch for a prevailing south-west wind direction.

Irrigation scheduling of threshold canopy temperature controlled treatments was controlled by two 4° field-of-view IRTs viewing the canopy perpendicularly from a 45° angle from the north and south sides. Additional information on temperature measurement and data recording are reported in Wanjura et al. (1992).

The following threshold canopy temperatures were used: 28, 30, and 32 °C in 1988; 28 °C in 1989; 26, 28, and 30 °C in 1990; and 28 °C in 1991. The treatment whose irrigation was scheduled by a 28 °C threshold temperature (T 28 C) in each year was used as the reference "well-watered" treatment.

Amount of irrigation control time for different canopy temperature thresholds were calculated. Optimum time was the amount of time that temperatures were between 25–31 °C. Irrigation-control-time was the amount of time that canopy temperature exceeded different thresholds.

Results and discussion

Air and canopy temperatures

Frequency distributions of dry bulb air temperature at 2 m (AT) and canopy temperatures of the 28 °C treatment (T 28 C) measured during 24-hour periods are compared in Fig. 2. The most frequently occurring temperatures in all years were 19 °C and 18 °C, respectively, for AT and T28C over the period of day-of-year (DOY) 198–273. Above 19 °C, AT frequencies declined linearly to an upper limit temperature of 33 °C. Canopy temperature frequencies declined from 18 °C to 20 °C, stabilized between 20 and 28 °C, and declined again between 28 °C and 32 °C. Presumably transpiration cooled the canopy and maintained uniform temperatures in the 20 to 28 °C range. The steep decline above 28 °C coincides with the threshold canopy temperature of 28 °C which caused irrigation to be applied and reduced the occurrence of temperatures above the threshold value.

The frequency distribution of AT and T 28 C was also compared in the optimum temperature range between 25–31 °C. The daily period for making the comparison was restricted to those times when AT was 25 °C or higher and total solar radiation was above 200 W/m^2. These restrictions represent atmospheric conditions when well-watered plants were transpiring in response to evaporation demand. The amount of time that AT and T28C were in the optimum range was lowest in 1989, Fig. 3. Air temperatures between 25 and 31 °C were more uniformly distributed than T28C. The difference (T28C–AT) in daily time that temperatures were within 1 °C increments between 25 °C and 31 °C were statistically compared using a *T*-test (analysis not shown). These comparisons were significant, except when designated as "ns" in Fig. 3.

The effect of using the 28 °C threshold canopy temperature to apply irrigation is shown by comparing the cumulative times that T28C and AT were between 25–29 °C and 29–31 °C, Table 1. Cumulative time at temperatures from 25 through 28 °C for T28C was always greater than for AT; however, from 29 to 31 °C AT was always greater than T28C. Irrigating when canopy temperature exceeded 28 °C reduced the amount of time that the cotton canopy exceeded 28 °C compared to that for AT. Among years both AT and T28C were lowest in 1989. The only year effect on AT and T28C was a lower amount of time that these temperatures were in the range from 25–31 °C in 1989.

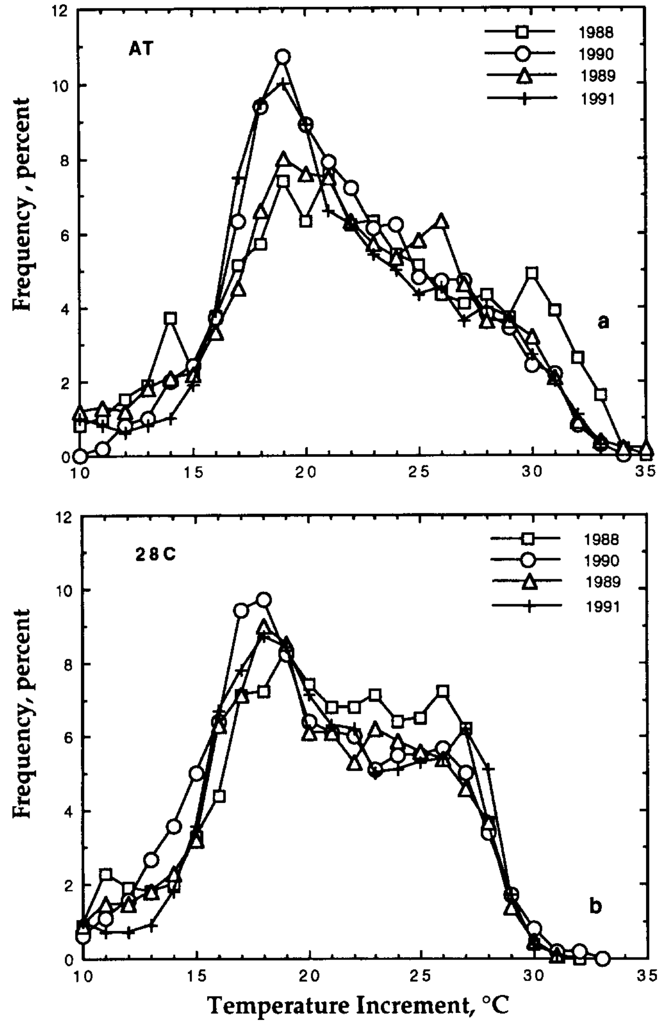

Fig. 2. Frequency distribution of air temperatures (AT) and canopy temperatures of the 28 °C threshold treatment (T 28 C) during 24-h periods for the interval DOY 198–273, 1988–1991

Optimum temperature

Optimum time was calculated using the time that either T 28 C or AT was within the range of 25–31 °C during the entire 24-hour period without filtering for any environmental condition. The distributions of AT and T28C within the optimum temperature range were different in all years, Fig. 4. The linear relationships between cumulative frequency with increasing temperature show that within the optimum temperature interval AT temperatures are uniformly distributed. Cumulative frequency of T28C increased most rapidly through the 27–28 °C increment but then decreased in comparison to AT. Times

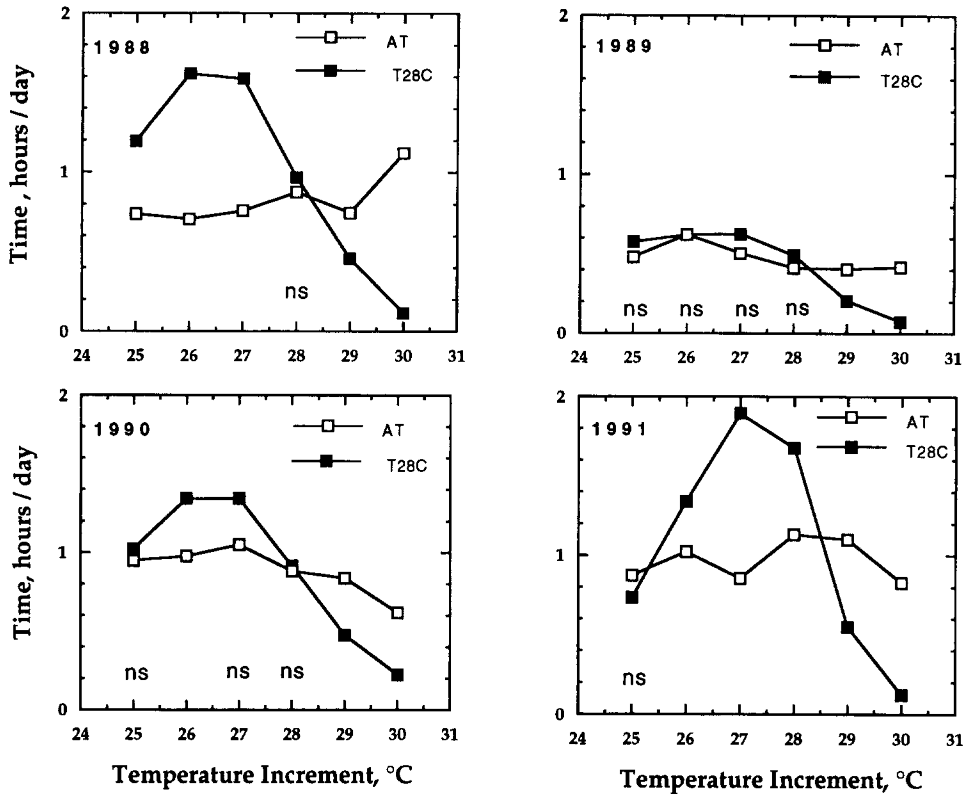

Fig. 3. Average daily time that air temperature (AT) and canopy temperature of the 28 °C threshold treatment (T 28 C) were within 1 °C intervals in the optimum temperature range (25–31 °C) for the interval DOY 198–273, 1988–1991. The daily periods were restricted to conditions when AT exceeds 25 °C and total radiation exceeds 200 W/m^2. Time per day is not statistically different where "ns" appears for the temperature increment

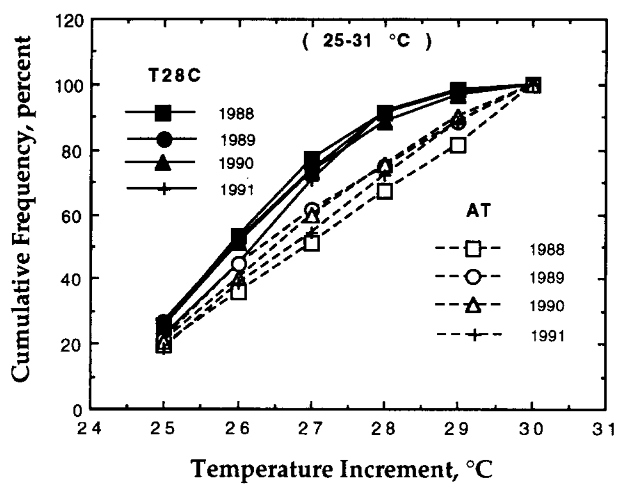

Fig. 4. Comparison of cumulative frequencies of air temperature (AT) and canopy temperature of the 28 °C threshold treatment (T 28 C) within the optimum temperature range for the conditions described in Fig. 3

Table 1. Cumulative time that canopy temperature of well-watered cotton (T 28 C) and air temperature measured at two meters (AT) were in the temperature range 25–31 °C while total radiation exceeded 200 W/m^2 and AT was equal to or greater then 25 °C during the period DOY 198–273

Year	Days	Total Time[a]	25–29 °C		29–31 °C	
			T 28 C	AT	T 28 C	AT
		Hours[b]				
1988	66	461	354	203	38	123
1989	60	200	14	121	17	49
1990	62	384	286	239	43	90
1991	55	378	311	214	37	106

[a] Total number of hours when AT exceeded 25 °C and total radiation was above 200 W/m^2

[b] Cumulative times for T 28 C and AT within each temperature range were significantly different except in 1989

at optimum temperature were similar for AT and T 28 C in each year except 1989 during DOY 198–273, Table 2. The largest difference in optimum time between AT and the T 28 C occurred in 1989 when AT was 109 h higher than T 28 C. The large difference in 1989 contrasts with all other years when differences were 30 h or less.

Irrigation control time

Irrigation control time was analyzed by comparing the different threshold temperature levels used to schedule irrigation. The year effect on irrigation control time for well-watered conditions was estimated by comparing values for T 28 C, Table 3. Irrigation control time had a range of 35 h (37%) compared with a range of 107 h (29%) in optimum time. The 37% range in irrigation control time would result in the same proportional range of application for a drip system with a constant irrigation rate.

The influence of threshold canopy temperature level on irrigation control time was estimated by comparing the different temperature thresholds used in 1988 and 1990, Fig. 5. Variations in irrigation control time among

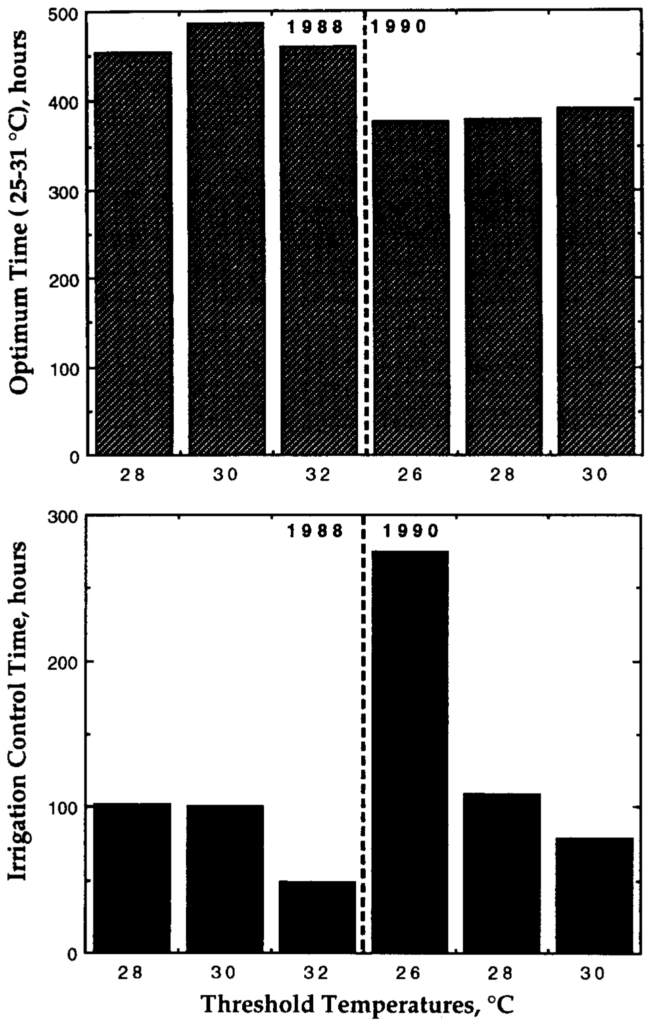

Fig. 5. Comparison of total optimum time and irrigation control time for threshold canopy temperature levels in 1988 and 1990 for the period DOY 198–273

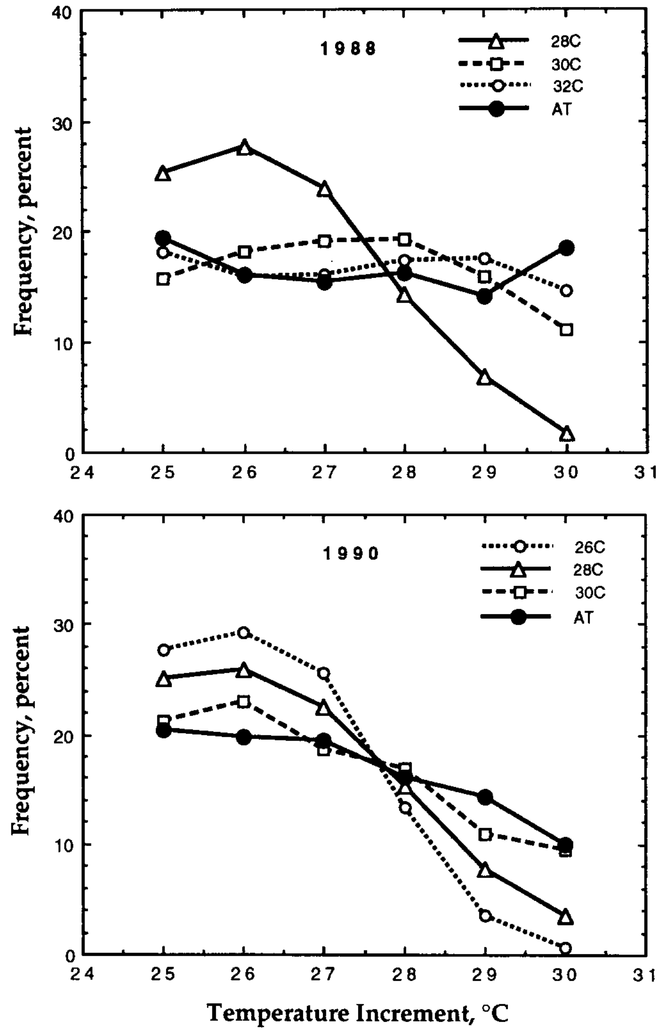

Fig. 6. Frequency distributions within the optimum temperature range (25–31 °C) for different threshold temperature levels and air temperature (AT) for the period DOY 198–273, 1988 and 1990

Table 2. Optimum time (25–31 °C) for canopy temperature of well-watered cotton (T28C) and for air temperature measured at two meters (AT) for the period DOY 198–273, 1988–1991

Year	T28C	AT	T28C	AT
	Hours		Percent of total time[a]	
1988	453	471	25	26
1989	366	475	20	26
1990	378	408	21	22
1991	437	414	24	23
Average	409	442	22	24

[a] Percentages were calculated based on 1824 total hours (76 days × 24-hours per day) during DOY 198 and 273

Table 3. Irrigation control time and optimum time for a 28 °C threshold canopy temperature controlled irrigation treatment (T28C) for the period DOY 198–273, 1988–1991

Year	Irrigation (Hours)	
	control time[a]	optimum time[b]
1988	102	453
1989	95	366
1990	109	378
1991	130	437

[a] Time above a threshold canopy temperature of 28 °C
[b] Time within the temperature range from 25–31 °C

threshold temperature levels were larger than their corresponding optimum times. In 1988 threshold temperatures of 28, 30, and 32 °C had a range of 54 h in irrigation control time which corresponded with a range of 32 h for optimum time. In 1990 irrigation control time of threshold temperatures 26, 28, 30 °C had a range of 196 h while optimum time had a range of only 14 h. Threshold temperatures between 26 and 32 °C were inversely related to irrigation control time. Higher threshold temperatures results in significantly less irrigation control time than lower temperatures but their optimum time was not reduced. Since optimum time was similar among different

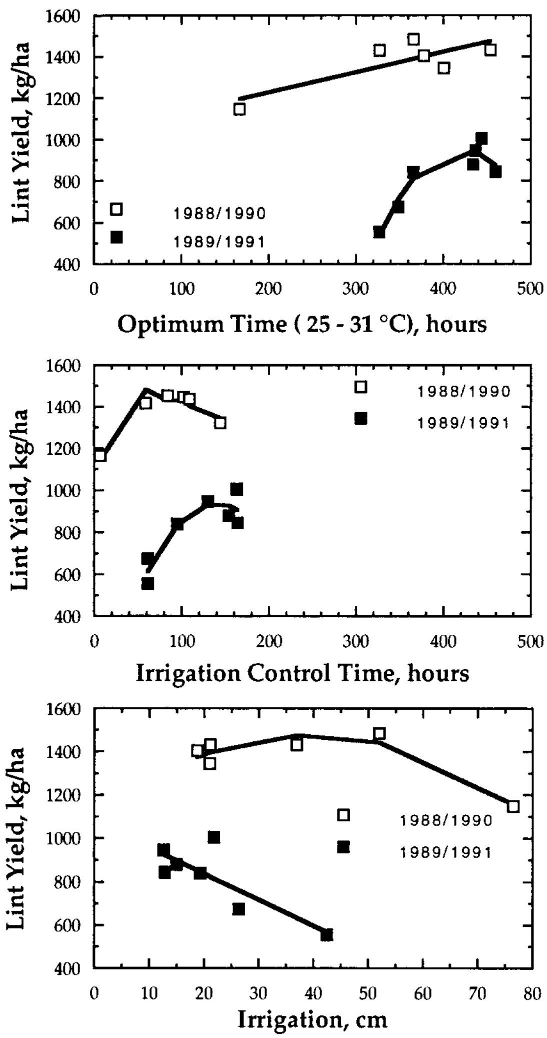

Fig. 7. Relationship of lint yield with optimum time, irrigation control time, and amount of irrigation during the period DOY 198–273 for high yield years (1988/1990) and low yield years (1989/1991)

threshold temperature levels but canopy temperatures were modified above the threshold temperature used for irrigation control it follows that the distribution of canopy temperatures within the optimum interval should be different among threshold temperatures, Fig. 6. In 1988 and 1990 threshold temperatures above 28 °C had few temperatures below 28 °C and more temperatures at or above 28 °C than did the lower threshold temperatures. The distributions of AT were more uniform than for any threshold canopy temperatures.

Lint yield

Well-watered irrigation treatments were used to minimize water stress effects on yield, Fig. 7. In this comparison, well-watered included threshold temperatures of 26 °C and 28 °C and a treatment that fully replaced soil water used on a weekly interval as measured by a neutron scattering technique. An obvious difference in years is apparent where 1988 and 1990 yields were higher than those in 1989 and 1991. Optimum time and irrigation control time had similar ranges in both the high and low yield years which suggests that they were not the causes for these large yield differences. The year effect on yield occurred outside the period, DOY 198–273, for which optimum time and irrigation control time were accumulated. The yield reduction in 1989 and 1991 resulted from plant damage caused by cool temperatures or thunder storms, (prior to DOY 198) that reduced plant vigor and population and late season cool temperatures that delayed maturity. The linear and second-order curves were computed using regression analysis. Criterion for choosing the best fit curve was that all regression model coefficients be statistically significant. Optimum time was linearly related to lint yield in high yield years (1988 and 1990) and nonlinearly in low yield years (1989 and 1991). Optimum time had the greatest effect on yield in the low yield years because low temperatures in 1989 and 1991 after DOY 243 did not allow the crop to fully mature. Irrigation control time was linearly related to yield in the low yield years and nonlinearly in the high yield years. Again, the effect of irrigation control time was greater in the low yield years because low temperatures after DOY 243 did not permit full crop maturity.

Total irrigation applied to the well-watered treatments, in direct proportion to differences in irrigation control time, during the period DOY 198–273, had a neutral effect on lint yield in the high yield years and a negative effect in the low yield years, Fig. 7. In the high yield years well-watered treatments received adequate irrigation during DOY 198–273 with some treatments being excessively irrigated. In low yield years irrigation amounts that showed a neutral effect in the high yield years decreased yield. Since one of the differences between high and low yield years was a shortened growing season, it is a reasonable assumption that the higher irrigation amounts applied in low yield years slowed crop maturity and reduced yield.

Conclusions

Correct application of threshold temperature controlled irrigation scheduling requires the crop to be thermally adapted to its growing environment and the threshold temperature must be appropriately selected to result in an amount of irrigation (water stress level) that is compatible with efficient production. The 28 °C threshold canopy temperature which results in a well-watered crop condition had maximum daily irrigations that ranged from 10–12 mm during the four years of this study. These irrigations were applied through a drip irrigation system where the average application rate varied from 1.5 to 2.1 mm/h. Daily potential evapotranspiration estimated by the Penman-Monteith combination method for a well watered short grass surface described in Jensen et al. 1990 averaged 7 mm/day during the period DOY 198–273. Thus, the irrigation system and scheduling procedure had the capability of completely supplying the full evapotranspiration demand. The irrigation scheduling method used in this study resulted in frequent irrigations. Small frequently applied irrigations are an effective and efficient method of irrigation (Bordovsky et al. 1992; Radin et al. 1989).

Different threshold canopy temperature levels did not significantly change the amount of optimum time when canopy temperature was within the optimum temperature range from 25–31 °C, but the frequency distribution of canopy temperatures within the optimum range was altered. Controlling irrigation scheduling with different threshold temperature levels changed the amount of irrigation control time and quantity of irrigation. Irrigation control time and optimum time were positively related to cotton lint yield.

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