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Environmental profile and critical temperature effects on milk production of Holstein cows in desert climate

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Abstract. The environmental profile of central Arizona is quantitatively described using meteorological data between 1971 and 1986. Utilizing ambient temperature criteria of hours per day less than 21° C, between 21 and 27° C, and more than 27° C, the environmental profile of central Arizona consists of varying levels of thermoneutral and heat stress periods. Milk production data from two commercial dairy farms from March 1990 to February 1991 were used to evaluate the seasonal effects identified in the environmental profile. Overall, milk production is lower during heat stress compared to thermoneutral periods. During heat stress, the cool period of hours per day with temperature less than 21° C provides a margin of safety to reduce the effects of heat stress on decreased milk production. Using minimum, mean and maximum ambient temperatures, the upper critical temperatures for milk production are 21, 27 and 32° C, respectively. Using the temperature-humidity index as the thermal environment indicator, the critical values for minimum, mean and maximum THI are 64, 72 and 76, respectively.

Key words: Environmental profile – Heat stress – Critical temperatures – Milk production

Introduction

Summer weather in the desert southwest of the United States is characterized by high daytime temperatures and intense solar radiation associated with low relative humidity, while nights are warm. Although night-time temperatures during winter may drop below freezing, afternoons are sunny and warm (Schmidli 1986). The low number of nights with freezing conditions eliminates the need for barn housing to protect dairy cows from cold; therefore extensive housing systems are typical. Cows are housed in corrals, which are usually not enclosed but have overhead shade to protect from direct solar radiation. Dairy farms also tend to be large. In hot weather, shade structures and their associated modifications (Armstrong et al. 1985; Igono et al. 1987; Ingraham et al. 1979; Wiersma et al. 1984) in addition to nutrient provision (Coppock 1983; Huber and Higginbotham 1986) form the essential components of heat stress management.

Air temperature and humidity are commonly used as criteria to express daily weather conditions, but are modified by wind, precipitation, and solar radiation. The ambient temperature below which the rate of heat production of a resting homoeotherm increases to maintain thermal balance is the lower critical temperature. The upper critical temperature is the ambient temperature above which thermoregulatory evaporative heat loss processes are recruited. The ambient temperature range within these defined limits is the thermoneutral zone. Within the zone of thermoneutrality, minimal physiological costs and maximum productivity normally are achieved (Berman et al. 1985; Johnson 1987; Johnson et al. 1962).

An environmental profile provides baseline data on which to estimate average expected climatic conditions, their variation and the duration of any extremes. Such knowledge is necessary for understanding animal responses to environmental conditions and in assessing the need to expend economic and energy resources in order to improve the climate for animal production. Although the effects of the Arizona desert climate on dairy cattle have been extensively studied, the main areas of research have been reproduction (Monty and Garbareno 1978; Monty and Wolff 1974; Stott and Wiersma 1973, 1976; Vaught et al. 1977; Wise et al. 1988; Wolff and Monty 1974), housing systems (Armstrong et al. 1985; Wiersma et al. 1984), and coat color (King et al. 1988). This study relates milk production to critical temperatures. In addition, the environmental profile is quantitatively described to allow for practical evaluation of environmental limitations to lactation, growth, and reproduction.

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Materials and methods

Meteorological data of central Arizona using a data base of records obtained between 1971 and 1986 (Schmidli 1986) were analyzed to provide a quantitative description of the environmental profile. Using critical temperature estimates in the literature (Berman et al. 1985; Brody et al. 1955; Rodriquez et al. 1985; Sharma et al. 1988) as a guide, the daily ambient temperature (t_{db}) was grouped into weather periods for each day to enable an in-depth description of the diurnal pattern of t_{db}. Hours per day of t_{db} less than 21° C are designated as "cool", between 21.1 and 27° C as "warm", and more than 27.1° C as "hot".

Milk production from two commercial dairy farms near the metropolitan city of Phoenix were used to evaluate the effect of climate on milk production. At the Arizona Dairy Company (ADC) at Higley, Arizona, daily milk production data were collected. The milking herd consists of 4400 Holstein cows; milking is three times daily. Animals are cooled between 0830 and 1900 hours using evaporative coolers (Korral Kool, Mesa, Ariz.) which are set to turn on when t_{db} is at or above 30° C; this occurs in late April to early May. Feeding management at ADC includes free choice of grain in the milking parlor in addition to a complete mixed ration fed in outside mangers. Three different outside rations are fed depending on the stage of lactation, with variation throughout the year in response to total intake, commodity cost, and availability. An average ration consists of 11.3 kg grain, 1.1 kg cottonseed meal containing vitamin-mineral premix, and 10 kg hay equivalent in the form of corn silage, alfalfa silage, soilage, and hay cubes. Data of daily production of all milking cows in this study are from March 1989 to April 1990.

The second dairy farm is K & L Dairy Ltd. (KLD), Gilbert, Arizona. Milk weights on Dairy Herd Improvement Association (DHIA) test days for the same period outlined for ADC form the data set. Animals are grouped according to production level, an average of 216 cows are milked daily, and milking is three times daily. Shade conditions are available by choice, and no other specific cooling aid is available. Using days in milk (DIM), animals are grouped into "early" (1–100 days), "mid" (101–200 days) and "late" (>200) stages of lactation. Data for animals with high somatic cell counts and clinically sick animals were excluded from the analysis.

Data were analyzed using least square analysis of variance to quantify environmental effects on milk production. Weather data used in the analyses were of relative humidity, maximum, minimum, and mean dry bulb temperature during the period of study (March 1989 to April 1990). The temperature-humidity index (THI) was calculated from values of relative humidity (RH, decimal) and dry bulb temperature (°F), using the following equation of Kelly and Bond (1971): $THI = t_{db} - [(0.55 - 0.55\ RH)(t_{db} - 58)]$. Linear and polynomial regressions were used to examine the relationship between environmental variables and milk production depending on which equation has the highest r-value. Statistical significance was set at $P \leq 0.05$.

Results and discussion

Environmental profile

Figure 1 illustrates the annual pattern of diurnal t_{db} cycles based on data for 1971–1986. Throughout January, t_{db} is less than 21° C per day with an average of 12.1° C. In February, the 2 h between 1600 and 1800 h are warm while the rest of the day is cool. Except for the 6 h between 1400 and 2000 h in March which are warm, the days are mostly cool. For April–June, the mean diurnal pattern of t_{db} consists of cool, warm, and hot components. In April, the hours between midnight and 0900 h

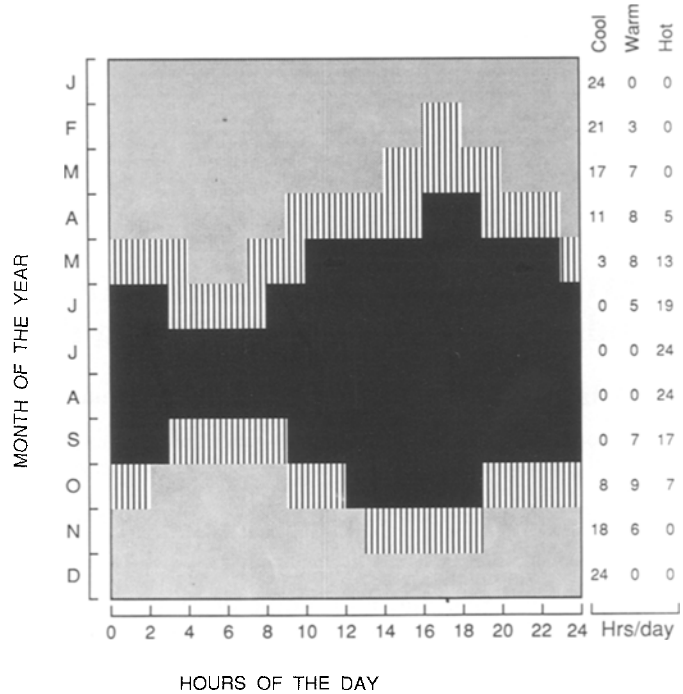

Fig. 1. Annual pattern of diurnal ambient temperature for Phoenix, Arizona. ▩ ambient temperature less than 21° C; ▥ ambient temperature between 21.1 and 26.9° C; ■ ambient temperature greater than 27° C. Hourly temperature data used to compute monthly means

are cool. Warm conditions prevail between 0900 and 2300 h, with a hot period of 4 h sandwiched between 1600 and 1900 h. In May the number of cool hours per day is drastically reduced to the period of 3 h between 0400 and 0700 h; the remainder of the day is warm or hot (1000 to 2300 h).

Temperatures during June to September are unique in several respects; for example, all hours of each day experience t_{db} of more than 21° C. This suggests that the ability of the animal to dissipate during the following night the heat gained from the previous day, may be compromised. Studies of cows exposed to simulated summer diurnal ambient temperature cycles for Phoenix, Arizona showed that if t_{db} did not decrease below 21° C during the night, the rectal temperature was usually above 39° C and did not return to normal before the next daytime t_{db} increase (Scott et al. 1983). However, the animals were able to withstand relatively high daytime temperatures when night-time temperatures were below 21° C, which permitted them sufficient thermal recovery via dissipation of accumulated body heat. Shishido et al. (1983) compared the effects of high temperature with a diurnal cycle to constant high temperature on milk production of Holstein heifers in a climatic laboratory. They concluded that the minimum temperature in hot conditions moderated the effects of heat stress on milk production.

The occurrence of a "natural heat laboratory" was observed during the months of July and August over a 62-day period when t_{db} is greater than 27° C. Also, during these months, there are about 5 to 7 h per day

Table 1. Diurnal pattern of monthly ambient temperature and relative humidity of central Arizona

Month	Ambient temperature, °C				t_{db}* <21		t_{db} =21–27		t_{db} >27		Relative humidity, %		
	Max	Min	Mean	Range	Mean	h/day	Mean	h/day	Mean	h/day	Max	Min	Mean
Jan.	18.6	6.3	12.1	12.3	12.1	24	0	0	0	0	70.1	31.7	51.7
Feb.	21.5	8.3	14.6	13.2	13.6	21	21.3	3	0	0	61.7	25.2	43.7
Mar.	23.5	11.3	17.3	12.2	15.1	17	22.5	7	0	0	56.6	24.0	39.8
Apr.	28.2	14.8	21.6	13.4	17.2	11	24.0	8	27.7	5	42.2	15.2	27.3
May	33.4	19.7	27.0	13.7	20.0	3	23.5	8	30.8	13	35.1	12.7	22.3
June	39.4	24.9	32.6	14.5	0	0	25.8	5	34.4	19	28.9	10.6	18.2
July	40.5	28.9	34.7	11.6	0	0	0	0	34.7	24	43.7	19.6	30.9
Aug.	39.3	27.9	33.5	11.4	0	0	0	0	33.5	24	48.1	21.8	34.1
Sep.	36.6	24.8	30.5	11.8	0	0	25.6	7	32.5	17	47.8	22.2	34.6
Oct.	30.1	18.2	23.7	11.9	19.2	8	23.6	9	29.1	7	52.1	23.5	38.7
Nov.	23.3	10.5	16.4	12.7	13.7	18	22.4	6	0	0	59.9	25.5	43.7
Dec.	19.0	6.9	12.1	12.2	12.1	24	0	0	0	0	68.7	31.0	51.7

* t_{db}, dry bulb temperature in °C

Table 2. Characterization of environmental temperature of central Arizona, which was used to evaluate the effects of critical temperature on milk production of Holstein cows

Phase	Period		Ambient temperature criteria[a]	Remarks
	t_{db}* rise	t_{db} fall		
I	January	December	cool	Few chances for heat stress because no heat period normally encountered
II	February and March	November	cool to warm	Animal may get warm but not heat-stressed
III	April and May	October	cool, warm, and hot	Animal encounters heat stress but normally has sufficient opportunity to lose at night all heat gained from the previous day
IV	June	August	warm to hot	Definite heat stress encountered with reduced chances to lose heat gained from previous day
V	July	September	hot	Chronic heat exposure with very poor chances of completely dissipating heat gained from previous days

* t_{db}, ambient dry bulb temperature
[a] Criteria: cool, t_{db} less than 21° C; warm, t_{db} between 21 and 27° C; hot t_{db} greater than 27° C

of t_{db} greater than 39° C, which is higher than a cow's normal body temperature (38.5° C). In September, the t_{db} decreases; the 7 h between 0300 and 1000 h are warm while the remaining 17 h are hot. In addition, in October, approximately one-third of the day is cool, another third is warm, and the last third is hot. Ambient conditions in November are analogous to March while December conditions are similar to January.

The number of hours per day of t_{db} is categorized as "cool", "warm", and "hot" monthly and values of relative humidity for each month of the year are given in Table 1. Mean t_{db} increases gradually from a baseline value of 12.1° C to a peak of 34.7° C in July, representing a rise of 22.6° C with an average monthly rise of 3.8° C. Following the July peak, the mean t_{db} declines each succeeding month and return to the baseline value in December. Relative humidity is generally low; mean values decrease from a maximum average of 51.5% in January to 18.2% in June. The local 'monsoon' season, which begins in July is associated with a rise of RH from 28.9% in June to 43.7%. The monsoon continues until September; the weather is humid during this period. Overall, maximum relative humidity occurs at night and increases following a thunderstorm.

Table 2 summarizes the climatic periods identified in this study. The environmental profile allows for careful delineation of periods based on meteorological factors. One significance of this type of weather analysis is in experimental design and data interpretation for enhanced understanding of physiological responses. For example, using mean t_{db} as shown in Table 1, it is reasonable to characterize the months of July to September as a hot period. However, the months of July and August have t_{db} greater than 27° C for 24 h per day while June and September experience 5 to 7 h per day of t_{db} less than 27° C. Experimental design should give cognizance to such differences in diurnal t_{db} classifications if the goals of the study include partitioning of between-period differences, which may significantly influence physiological responses and productivity.

The diurnal pattern of the temperature-humidity index (THI) is given in Table 3. Because of the low relative humidity (Table 1), the diurnal pattern of THI mirrors the t_{db} pattern. Between January and April, THI values are less than 72. In May, 10 h of each day experience THI greater than 72, but in June this increases to 18 h per day. During July and August, average THI is at or above 80 for 24 h per day. Hours per day of THI values greater than 72 drop to 20 in September and 6 in October; thereafter, no THI values greater than 72 per day are observable for the rest of the year. The work of Johnson et al. (1962) established that at THI values greater than 72, Holstein cows experience demonstrable signs of heat stress. Using THI as the indicator of heat stress, Holstein cows in the central Arizona desert would encounter heat stress between May and October of each year.

Table 3. Diurnal pattern of the monthly temperature-humidity index (THI)* for central Arizona

Month	THI			THI <72		THI >72	
	Mean	Min	Max	Mean	h/day	Mean	h/day
Jan.	51.4	44.5	61.0	51.4	24	0	0
Feb.	57.0	50.2	63.8	57.0	24	0	0
Mar.	59.9	53.9	65.9	59.9	24	0	0
Apr.	64.0	57.3	70.3	64.0	24	0	0
May	70.0	62.9	75.9	66.7	14	74.7	10
June	76.1	68.8	82.2	70.0	6	78.1	18
July	80.9	75.9	85.9	0	0	80.9	24
Aug.	80.0	75.0	85.0	0	0	80.0	24
Sep.	76.2	71.1	81.6	71.3	4	77.2	20
Oct.	68.0	62.4	73.9	66.2	18	73.3	6
Nov.	59.2	53.0	65.9	59.2	24	0	0
Dec.	54.9	48.7	61.4	54.9	24	0	0

* $THI = t_{db} - \{(0.55-0.55\ RH)(t_{db}-58)\}$; t_{db}, dry bulb temperature, °F; RH, relative humidity, decimal

Arizona Dairy Company (ADC) farm

Figure 2 illustrates the relationship between daily milk yield and t_{db} at ADC; provision of evaporative cooling was begun in late April when t_{db} reached 30° C during the daytime. A gradual rise in both minimum and maximum t_{db} is evident from March 1, 1989 (day 1) to a peak by mid-July (day 150), after which the values declined daily until mid-December (day 325). Between mid-December and the beginning of March, marked varia-

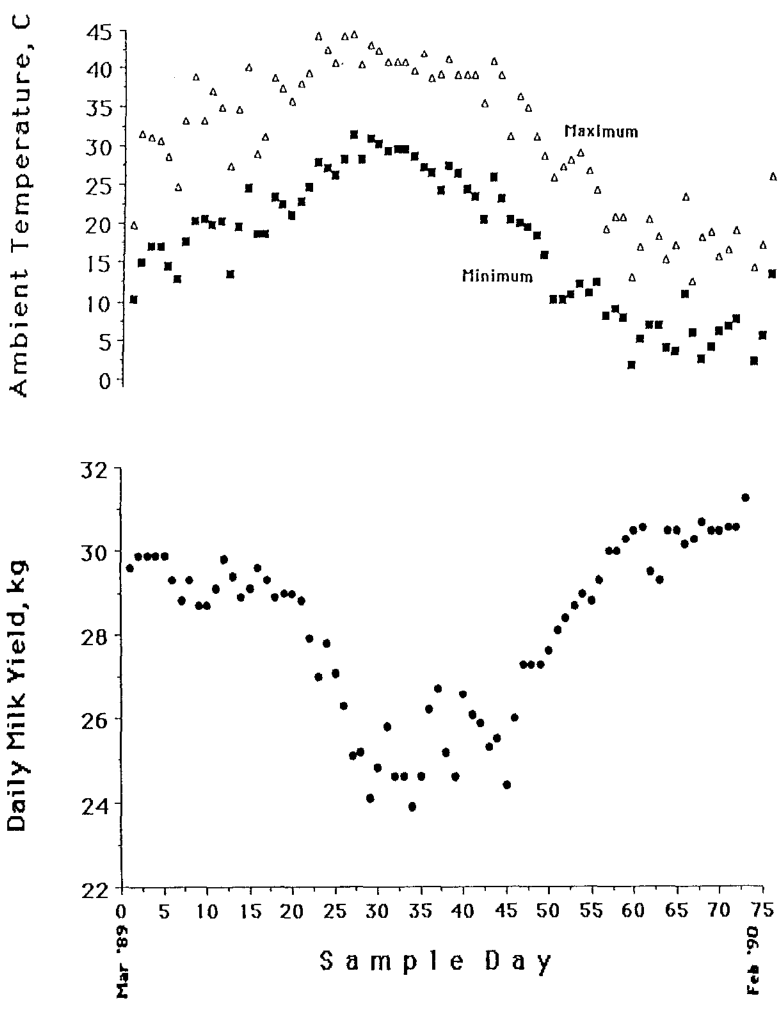

Fig. 2. Fluctuations in 5-day moving average of maximum and minimum ambient temperatures (°C) and milk yield (kg/day) at the Arizona Dairy Company (ADC), Higley, Arizona

tion of ambient temperature was not observed. In general, the thermal environment during the year of this study was similar to the pattern discussed in the environmental profile. Milk production averaged 30.3 kg/day in March but declined to 29.6 kg/day between early April (day 30) and early June (day 110). A precipitous drop in daily milk yield occurred after mid-June (day 115) until late August (day 175). During this period, average daily milk yield dropped from 28.5 to 24.5 kg/day. Between mid-July (day 150) and early October (day 225) wide fluctuations in daily milk yield were apparent. From mid-October (day 230) to mid-December (day 300) daily milk yields recovered from 27.5 to 30 kg/day. Thereafter, daily milk yield averaged 31.0 kg/day, which is comparable to the yield obtained in March.

Maximum mean daily milk yield (30.3 kg) occured during the 61 days of the cool t_{db} conditions in January and December. On days classified as cool to warm t_{db}, as in February, March, and November, average daily milk production (29.6 kg) showed a 2.3% or 0.7 kg/day decline. On a large dairy farm like ADC with a rolling herd average of 4400 cows, the economic significance of a decreased yield of 0.7 kg/day for 89 days of the cool to warm t_{db} period becomes obvious. However, during the cool, warm, and hot diurnal t_{db} conditions as observed in April, May, and October, average daily milk production (28.2 kg) was lower ($P<0.05$) than for days classified as cool t_{db} or cool to warm t_{db}. Days of warm to hot t_{db}, which occur in June and September, experienced a 10.9% decline in average daily milk production compared to the cool t_{db} periods. The 16.5% or 5.0 kg/day decline in daily milk yield during the hot t_{db} period of July and August compared to cool t_{db} represents the greatest ($P<0.01$) decline of daily milk production between the three t_{db} categories.

Figure 3A illustrates the negative correlation ($P<0.05$) between mean monthly milk production at ADC and t_{db}. Daily milk production declined by 0.175, 0.183, and 0.170 kg for each unit rise in maximum, minimum and mean temperature respectively. Figure 3B shows the relationship using THI as the indicator of the thermal environment to incorporate the effects of humidity. The decline of average milk production for each unit of THI rise was 0.163, 0.146, and 0.158 kg for maximum, minimum, and mean THI respectively. The correlation coefficients using either t_{db} or THI as the indicator of the thermal environment are similar at ADC.

K & L Dairy (KLD) farm

The thermal environment at KLD was similar to that described for ADC. Figure 4 illustrates the effect of the thermal environment and number of lactations on the milk production of cows grouped according to stage. There is a remarkable similarity in the pattern for the thermal effects on milk yield; therefore, the description for Fig. 4A serves as the model for the various lactation numbers. Between January and April, the levels of average milk production were similar, as indicated by the overlapping error bars, the range of mean milk production being between 31 and 28 kg/day. There was a trend for declining milk yield between March and May. Milk yield in June was similar to yields in April and May but different ($P<0.05$) from January, February, and March. Average milk yield in June dropped ($P<0.05$) precipitously from 27.6 to 20.0 kg/day in July. Thereafter, a stepwise ($P<0.05$) rebound occurred; in August average milk production was 23.0 kg/day compared to 26.5 kg/day in September. Milk yields in October and November were similar to that in September; in December, full yield recovery was attained.

Ambient temperature significantly ($P<0.05$) affected average daily milk production at KLD. Maximum daily milk production (33.2 kg) was obtained during the 61 days of January and December, which constitute the cool diurnal t_{db}. The 89 days of February, March, and November which make up the cool to warm diurnal t_{db}, experience a 2.5 kg/day or 7.5% drop ($P<0.05$) in daily milk yield compared to the period of cool diurnal t_{db}. Milk production during the 91 days of April, May, and October, which constitute the cool, warm, and hot diurnal t_{db} (29.5 kg/day) was similar to the cool to warm diurnal t_{db} (30.7 kg/day). Compared to the cool diurnal t_{db}, daily milk production during the cool, warm, and hot diurnal t_{db} showed a 3.7 kg/day or 11.1% decline ($P<0.05$). During the 60 days of the warm to hot diurnal t_{db} of June and September, daily milk yield (28.5 kg) was 5.7 kg or 17.2% less ($P<0.05$) compared to the cool t_{db}-diurnal. Milk production per day was lowest (21.7 kg/day; $P<0.05$) during the 61 days of the hot t_{db} period; compared to cool diurnal t_{db}, this was a yield reduction of 34.6% or 11.5 kg/day.

Diurnal t_{db} significantly ($P<0.01$) influenced milk production at different stages of lactation (Table 4). Average milk yield for cows in early lactation during the cool (32.0 kg), and the cool to warm (31.4 kg) diurnal t_{db} were similar but yields were higher ($P<0.05$) than the yield during the cool, warm, and hot diurnal t_{db} (30.6 kg). The lack of a cool period during the warm to hot t_{db} period in June and September indicated a reduced opportunity to lose body heat completely at night; this was associated with a reduction ($P<0.05$) of mean daily milk yield (29.4 kg). Average daily milk yield for cows in early lactation was lowest ($P<0.05$) during the hot diurnal t_{db} (23.2 kg).

For cows in mid-lactation, maximum average milk yield was obtained during the cool diurnal t_{db} (28.8 kg); this yield dropped ($P<0.05$) to 27.1 kg/day during the cool to warm diurnal t_{db}. However, the daily milk yields during the cool to warm and cool, warm, and hot diurnal t_{db} categories are similar but differ significantly ($P<0.05$) from the yield obtained during the warm to hot t_{db} period. The lowest ($P<0.05$) daily milk yield for cows in mid-lactation occurred during the hot diurnal t_{db} (22.1 kg). Within the t_{db} categories, average daily milk yield was higher ($P<0.05$) for cows in early than mid-lactation. During the late stage of lactation, average daily milk production was similar for all weather periods except during hot diurnal t_{db} weather when the average daily yield (18.9 kg/day) was less ($P<0.05$).

The relationship between mean daily milk yield, t_{db}

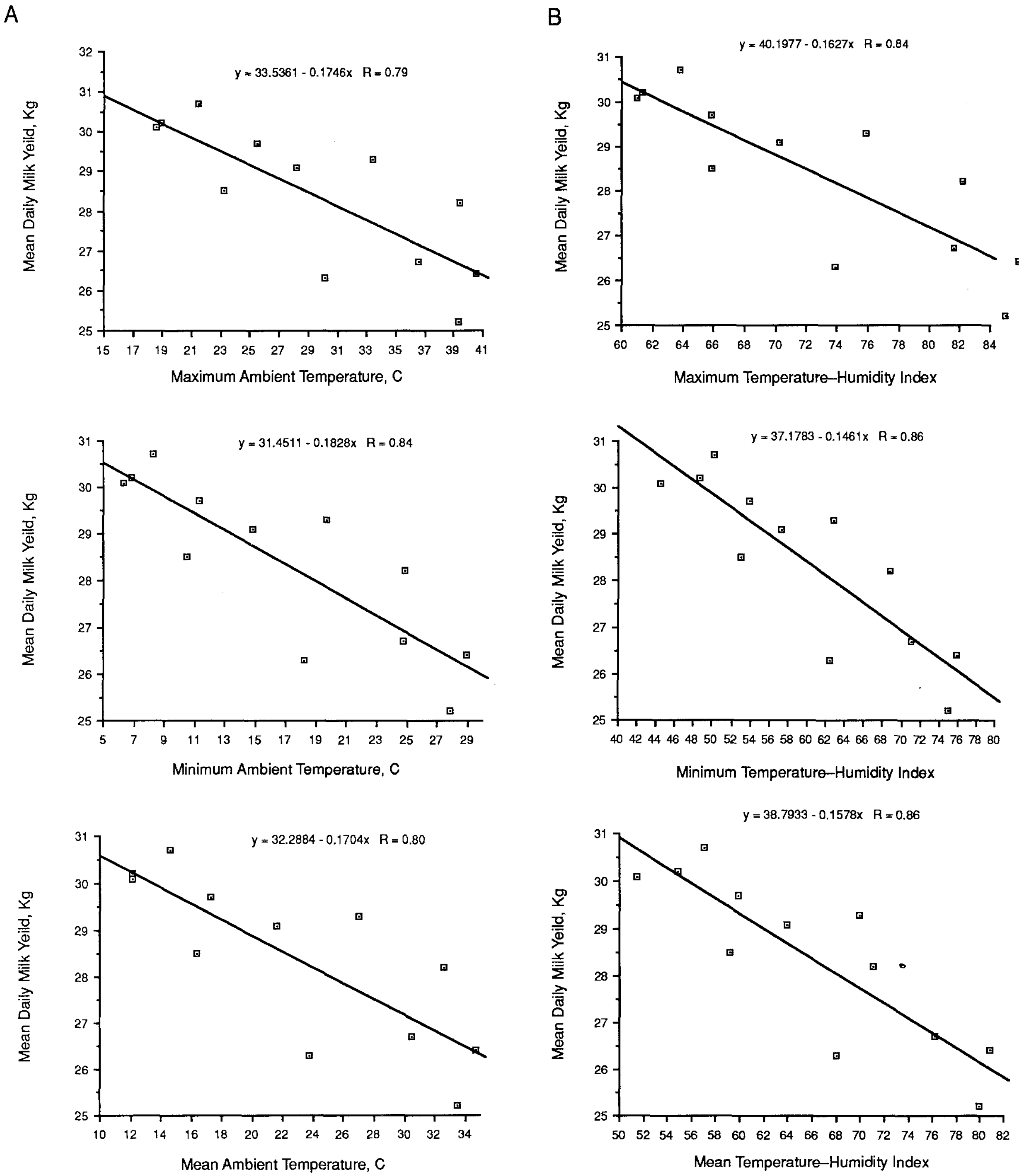

Fig. 3A and B. Relationship of **A** ambient temperature (°C) and **B** mean daily milk yield (kg/day) to the temperature-humidity index at Arizona Dairy Company, Higley, Arizona

and THI is shown in Fig. 5. A marked decline of daily milk production occurred when the minimum t_{db} was greater than 21° C, when the maximum t_{db} was greater than 32° C, or when the mean t_{db} was greater than 27° C (Fig. 5A). Thus, the critical minimum, maximum, and mean t_{db} values for declines in milk yield for lactating Holstein cows in the desert of Arizona are 21, 32, and 27° C, respectively. Table 1 shows that between January and April, the maximum t_{db} is less than 32° C, the minimum t_{db} is less than 21° C, while the mean t_{db} is less

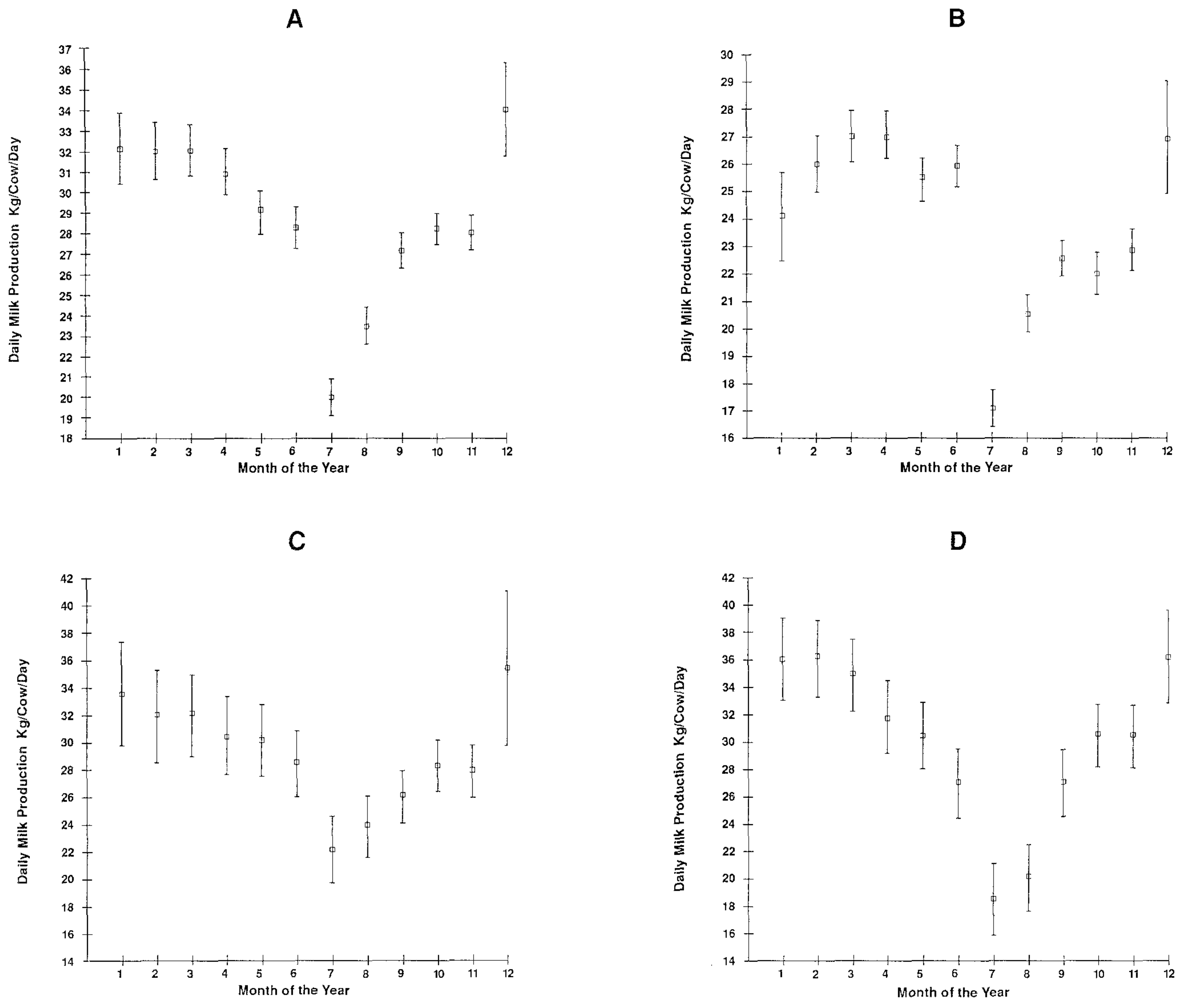

Fig. 4A–D. Monthly variation in mean daily milk yield for **A** all cows, and cows in **B** first, **C** second, and **D** third and above lactation numbers at K & L Dairy farm, Gilbert, Arizona

Table 4. Effect of diurnal temperature classification on milk production (kg/day) at different stages of lactation (KLD farm)

Temperature classification	Stage of lactation								
	Early			Mid			Late		
	Mean	SE	*n*	Mean	SE	*n*	Mean	SE	*n*
Cool	$32.0^{A,a}$	0.01	120	$28.8^{A,b}$	0.01	80	ND	ND	ND
Cool to warm	$31.4^{A,a}$	0.02	337	$27.1^{B,b}$	0.03	209	$22.3^{A,c}$	0.07	70
Cool, warm, and hot	$30.6^{B,a}$	0.02	360	$27.2^{B,b}$	0.02	257	$23.1^{A,c}$	0.05	95
Warm to hot	$29.4^{C,a}$	0.03	249	$26.7^{C,b}$	0.03	189	$22.8^{A,c}$	0.02	133
Hot	$23.2^{D,a}$	0.03	236	$22.1^{D,b}$	0.03	169	$18.9^{B,c}$	0.03	158

^{A,B,C,D,E} Means within columns having dissimilar superscript letters are significantly different ($P<0.05$)
^{a,b,c,d} Means within rows having dissimilar superscript letters are significantly different ($P<0.05$)
n, Number of observations; ND, no data

than 27° C. In May, however, when the maximum t_{db} is greater than 32° C and the mean t_{db} is 27° C, average daily milk production is less ($P<0.05$) than for January, February, and March. These observations explain the similar levels of milk production obtained between January and April.

Brody et al. (1955) in a study of the effects of the diurnal temperature cycle on cows in a climatic chamber

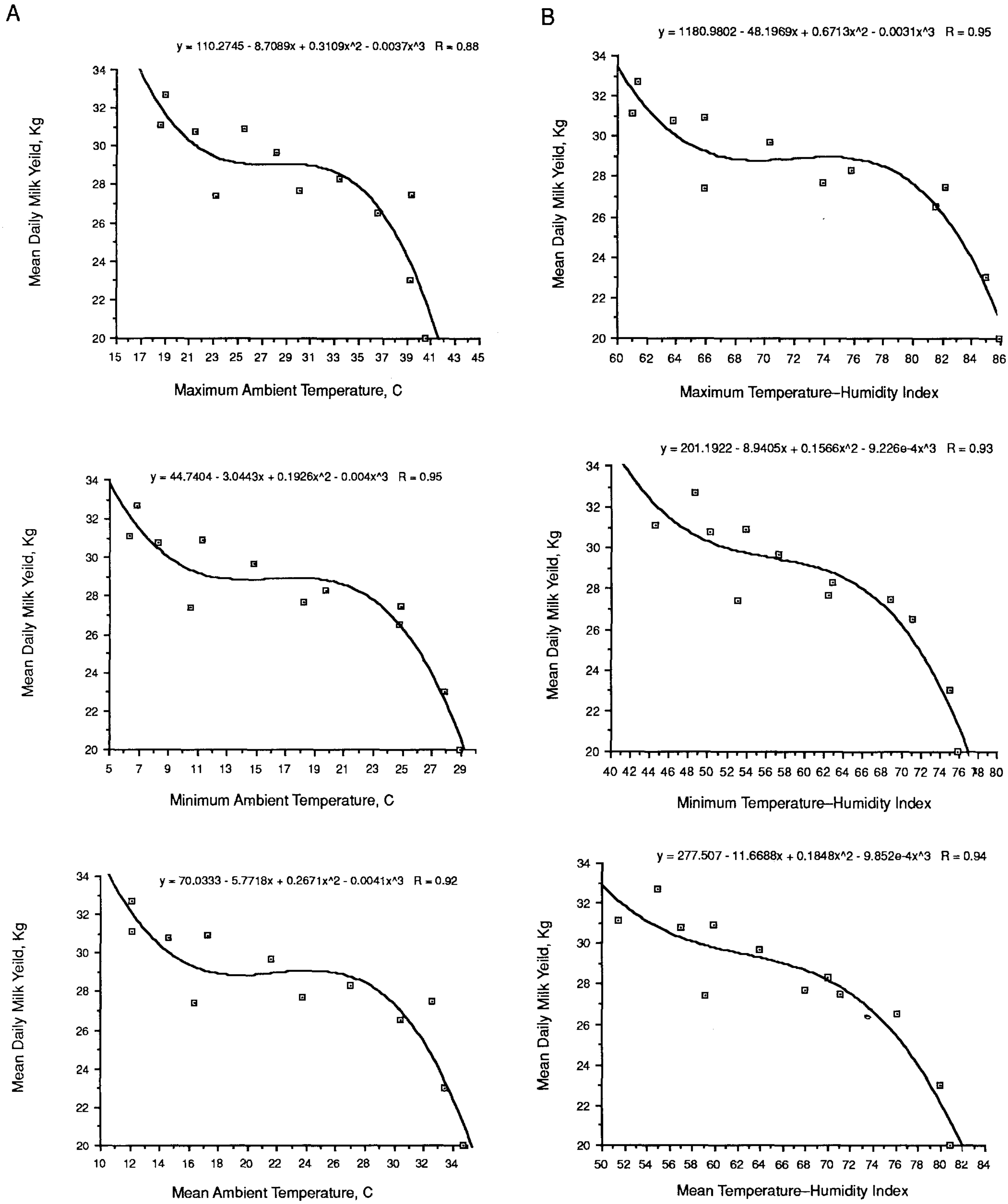

Fig. 5A and B. Relationship between **A** mean daily milk yield and ambient temperature, and **B** mean daily milk yield and temperature-humidity index at K & L Dairy farm, Gilbert, Arizona

concluded that the best indication of heat stress an animal experiences may be estimated by the number of hours of heating above 26.6° C or cooling below 21.1° C. Berman et al. (1985) recalculated data published from the Missouri Climatic Laboratory on Holstein cows yielding 10–25 kg milk/day and found that body temperatures increased at t_{db} above 26° C. In their study on a commercial dairy farm in the subtropics of Israel, Berman et al. (1985) observed that rectal temperatures increased in the t_{db} range of 24–26° C irrespective of milk yield. In the warm, humid, subtropical climate of Florida, Rodriquez et al. (1985) and Sharma et al. (1988) reported significant a decline in milk production for Holstein cows with t_{db} values of more than 27° C. In a study during the summer in Maryland, Maust et al. (1972) reported that for Holstein cows there were significant negative correlations between milk yield and t_{db} greater than 27° C. In the present study we have also shown that in a hot, dry, desert climate, the upper critical temperature for Holstein cows at which a decline in milk yield occurred was at a mean t_{db} of 27° C.

It is customary to explain differences between studies in a climatic chamber and field studies by alluding to the differences between climatic chamber and natural conditions in terms of day-night fluctuations, wind speed, and solar radiation. However, the various studies in the climatic chamber and in field conditions ranging from hot, dry to hot, humid weather cited here all show the same range for the upper critical temperature of Holstein cows. This unanimity of results indicates a need for re-examination of earlier explanations and emphasizes the need for careful definition of the environment in order to minimize differences in results obtained from different environments, in addition to proper experimental design and a robust data base.

Figure 5B shows the relationship between daily milk production and THI. Milk production declined markedly with maximum THI greater than 76, minimum THI greater than 64, or mean THI greater than 72. Thus lactating for Holstein cows in the desert of central Arizona, critical maximum, minimum, and mean THI values for declines in milk yield are 76, 64, and 72, respectively. The mean critical THI value of 72 is in agreement with the climatic chamber data of Johnson et al. (1962) and the field studies of Ingraham et al. (1979) during the summer in Hawaii. The basis for this concordance of results may be the fact that in the computation of THI, various temperatures and humidities can be combined to produce a certain THI; thus, it is possible to compare THI data and animal responses at different locations.

One common feature of the cool (January and December), cool to warm (February, March, and November), and cool, warm, and hot (April, May, and October) t_{db} categories is a cool t_{db} component in the diurnal t_{db}. This suggests that even when t_{db} increases during the day, if a cool t_{db} period of less than 21° C occurs at night for 3–6 h, a decline in milk production may be minimized. During the warm to hot (June and September) and hot (July and August) t_{db} classifications, when diurnal t_{db} lacked a cool period with t_{db} less than 21° C, a marked decline in milk production occurred. These observations are substantiated by results of Shishido et al. (1983) in their evaluation of the effects of a diurnal temperature range of 22–36° C versus a constant temperature of 29° C on milk production of four pairs of dizygotic twin Holstein heifers in a climatic chamber. The effect of maximum daytime t_{db} was reported to be minimized by minimum t_{db} at night. In the study of Scott et al. (1983), non-lactating Holstein cows were exposed to a simulation of the Phoenix diurnal temperature cycle. Their data showed that the lack of t_{db} below 21° C during the night compromised the ability of cattle to dissipate stored daytime heat with a net effect of rectal temperatures above 39° C. However, when night-time cooling was provided so that t_{db} was at or below 21° C, the animals were able to maintain a rectal temperature below 39° C. The ability to attain heat balance at some time during each 24-h cycle is apparently critical for efficient performance.

Integration of environmental effects

Unlike the controlled environment of climatic chambers where a given set of weather conditions can be simulated for a desired period, the natural climate is characterized by a 24 h cycle of day-night weather patterns that vary from day to day and season to season. It is common practice and also probably more convenient to summarize daily and monthly average weather conditions; however, such data lack the necessary detail to provide the background information needed for proper interpretation and, hence, understanding of physiological responses. Available weather information needs to be collated to clarify the use of the thermal environment as a basis for physiological studies and interpretation of results obtained under field conditions. As shown in this study for central Arizona (Fig. 6), the 62 days of January and December may be described as an "optimum thermoneutral" period for milk production by Holstein cows. The 89 days of February, March, and November represent a "warm thermoneutral" period with high levels of milk production associated with a nonsignificant reduction in daily milk yield. The remaining 214 days or 58.6% of the year experience various levels of heat stress with temperatures above the upper critical temperature. Specifically, April, May, and October represent the only months during the period heat stress to experience hours of t_{db} less than 21° C, giving the animals a cool respite at night; these 92 days constitute a "mild heat stress" period. June and September experience a diurnal t_{db} pattern with no cool component; these 60 days make up a "moderate heat stress" period in association with a significant decline in milk production. July and August constitute a period of 62 days when a diurnal t_{db} pattern categorized as hot is experienced for 24 h per day; this is a period of "severe heat stress". As shown by the results of this study, the climate of central Arizona truly provides a "natural climatic laboratory" to study the physiological effects of heat stress on milk production.

For comparative purposes, mean daily milk production at ADC and KLD are given in Table 5. At both dairy farms, average daily milk production is significantly ($P<0.05$) influenced by the t_{db} period. Within the t_{db} classification, there is a remarkable similarity in yield for all temperature categories; the exception is the hot t_{db} period when yields at ADC (25.3 kg/day), where evaporative cooling is provided, are higher ($P<0.05$)

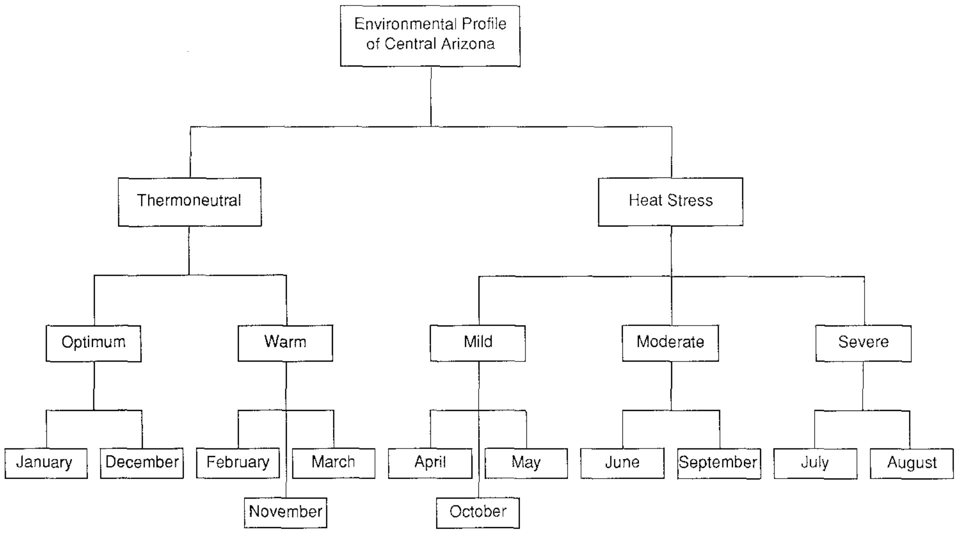

Fig. 6. Monthly groupings of the thermoneutral and heat stress periods of the environmental profile of central Arizona

Table 5. Mean daily milk production (kg/day) at Arizona Dairy Company and K & L Dairy (KLD) farms during the different periods of classifiable ambient temperature

Temperature classification	ADC			KLD		
	Mean	SE	n	Mean	SE	n
Cool	$30.1^{A,a}$	0.01	8285	$31.8^{A,a}$	07	200
Cool to warm	$29.6^{B,a}$	0.01	12739	$29.0^{B,a}$	0.01	616
Cool, warm, and hot	$28.2^{C,a}$	0.02	12542	$28.4^{B,a}$	0.01	712
Warm to hot	$26.9^{D,a}$	0.02	8206	$26.9^{C,a}$	0.01	571
Hot	$25.3^{E,a}$	0.02	8152	$21.7^{D,b}$	0.01	563

n, Number of observations
^{A,B,C,D,E} Means within columns having dissimilar superscript letters are significantly different ($P<0.05$)
^{a,b} Means within rows having dissimilar superscript letters are significantly different ($P<0.05$)

than at KLD (21.7 kg/day). These observations indicate the comparable ability of Holstein cows for milk production in the same environment. The differences in milk yield during the hot diurnal t_{db} period is attributable to the environmental modification: the use of evaporative cooling at ADC in periods other than the hot t_{db} period during summer is either not beneficial or is not being utilized to maximum effect. The latter supposition is more likely, in consideration of the fact that the cooling equipment at ADC is in operation daily between 0830 and 1900 h during summer. As shown clearly in Fig. 1, during the warm to hot t_{db} days of June and September, t_{db} is greater than 27° C until 0300 h. This leaves a balance of 8 h per day of the hot t_{db} period when the cooling facilities are not provided for the cows. Coping with heat stress during these hours may involve expenditure of energy which could have been used for milk production. Also during cool, warm, and hot t_{db} days in May, the hot t_{db} period extends to 2200 h; thus the animal still has to respond to 3 h of hot t_{db} per day. It is not clear whether the economics of operating the evaporative cooling facilities for more hours per day are justifiable. Some considerations include the cost of operating the equipment versus the return on milk production, a full understanding of the environmental profile for specific application, or both.

The relationship of both t_{db} and THI (Fig. 3) to milk production at ADC are linear in contradistinction to the curvilinear relationship for KLD (Fig. 5). The difference between the wet bulb and dry bulb temperature readings from a psychrometer, i.e. the wet bulb depression, gives an indication of the potential for lowering ambient temperature by evaporative coolers. The differences in June, July, August, and September were 16, 13.5, 12.3, and 11.4° C respectively. Thus, operating cooling equipment during the hot period would basically reduce the number of hours per day of t_{db} greater than 27° C and thereby attenuate the effects of the macroenvironment.

Conclusions

For both dairy farms, despite management differences, the highest daily milk production occurred during optimum thermoneutral periods characterized by t_{db} of less than 21° C for 24 h per day. Thus, Holstein cows in a desert climate approximate their maximum genetic potential for milk production during the optimum thermoneutral days of January and December. Decreasing the number of hours per day of t_{db} less than 21° C was associated with a decrease in milk production. Days without a t_{db} component providing hours with t_{db} of less than 21° C occur in June, July, August, and September and result in the most losses in milk production. These observations suggest that in a desert climate, the absence of a cool t_{db} component in the diurnal t_{db} removes a safety margin that minimizes the negative effects of the high thermal environment.

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