Interactions of Climatic Factors Affecting Milk Yield and Composition[1]

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ABSTRACT

Objectives were to evaluate effects of interactions of maximum temperature, minimum relative humidity, and solar radiation on milk yield and constituent traits. Effects of climate variables and their interactions were significant but small in most cases. Second order regression models were developed for several variables. Six were examined in detail: Holstein and Jersey milk yields, Holstein fat and Feulgen-DNA reflectance percent, and Jersey protein percent and yield. Maximum temperature had greatest influence on each response, followed by minimum relative humidity and solar radiation. Optimum conditions for milk production were at maximum temperatures below 19.4°C, increasing solar radiation, and minimum relative humidity between 33.4 and 78.2% (cool sunny days, moderate humidity). Maximum Holstein fat percent of 3.5% was predicted for maximum temperatures below 30.8°C, minimum relative humidity below 89%, and solar radiation below 109 Langleys; actual mean Holstein fat percent was 3.35%. Optimum climatic conditions for Jersey protein percent were at maximum temperature of 10.6°C with solar radiation at 300 Langleys and relative humidity at 16% (cool sunny days, low humidity). Because noteworthy interactions existed between climate effects, response surface methodology was suitable for determining optimum climatic conditions for milk production.

INTRODUCTION

Dairy animals are very sensitive to climatic variations and several reports (10, 11, 13, 14, 18, 25) demonstrated adverse effects of high air temperature, solar radiation, and relative humidity on animal production, feed efficiency, and reproduction. However, individual animal responses to climatic variation are dependent on several factors such as animal size, breed, color and texture of skin, individual degree of heat tolerance, nutritional status, and genetic potential for production (14, 16, 19).

Optimum milk yield and efficiency usually are obtained within the comfort zone of 5 to 22°C. Below 5°C often no appreciable declines in milk yield are noticed unless temperatures drop to about -15°C. However, even moderate increases in temperature above 25°C result in measurable declines in milk production (16). This reduction for cows exposed to high environmental temperatures has been attributed at least partially to heat-induced depression in feed intake (18, 19). Estimates of variance in lactation milk yield associated with temperature effects have ranged from 3 to 10% (15, 22), indicating the importance of climate as a limiting factor in milk production.

Although effects of ambient temperature on milk yield and fat percent have been well-documented (14, 16, 17, 18), little information exists on relative humidity and solar radiation. Effects of wet bulb temperature on production are not clear; combinations of temperature and relative humidity with the same wet bulb temperature had different effects on milk yield (14). Further, the methodology to determine optimum climatic conditions for milk pro-

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duction is not readily available. One approach could be to use response surface methodology (RSM) developed by Box et al. (4). Response surface methodology is a useful tool to find optimum operating conditions and to determine factors affecting the system under study (2, 3, 6). Response surface methodology has been used in numerous investigations (1, 8, 12, 20). Cragle et al. (7) and Chandler et al. (5) used RSM to obtain optimum survival conditions for spermatozoa in semen diluent.

This study was undertaken to quantify variation in milk yield and constituent traits due to climatic factors such as maximum temperature, minimum relative humidity, solar radiation, and their interactions, and to study the feasibility of using RSM to explore the optimum climatic conditions for milk and constituent production.

MATERIALS AND METHODS

Data utilized in this study were obtained from the University of Florida Agricultural Experiment Station herd at the Dairy Research Unit near Gainesville. Descriptions of data and data collection appear elsewhere (23, 24). The set of climatic measurements consisted of maximum temperatures recorded at 1.52 m above ground level, percent minimum relative humidity, and hemispheric solar radiation on a horizontal surface measured in Langleys. Briefly, production data were 22,212 records of Holsteins (11,092) and Jerseys (11,120) for 1959 to 1977 inclusive; each record represented the performance of a single cow on 1 d. Cows were sampled once monthly as a part of the regular DHI testing program. Climate measurements were for the day of the evening milk sample or weight. Data first were subjected to an extensive series of least squares analyses of variance to quantify genetic and environmental effects (24). For this study, the mathematical model for an individual observation for each breed included sire, daughter in sire, and lactation in daughter in sire, all of which were assumed to be random. Included in addition was a set of fixed effects: year, age of cow at test date, stage of lactation, stage of pregnancy, and the three climate measurements. Except for year, which was considered discrete, terms to the third order of polynomial regressions were included for the remaining fixed effects. Based on these analyses, it then was possible to evaluate interactions between climatic variables by RSM.

Analyses of the response surface models for each dependent variable for each breed were performed by techniques described by Cochran and Cox (6) and Myers (21). Briefly, this involved selection of a mathematical model and estimation of regression coefficients, followed by the analysis of the fitted surfaces. Location of the stationary points (SP) where the derivatives were simultaneously equal to 0 then were determined. To find the nature of the SP, the resulting regression equations then were transformed to canonical form, which contained only quadratic terms. The nature of response surface system was determined by observing the sign and magnitude of the latent roots of the canonical equations. If all latent roots were negative, responses at SP were assumed to be maximum. If all latent roots were positive, the response at SP was minimum. If latent roots differed in sign, the SP was minimax (saddle point). The response at SP was maximum for the variable with negative roots and minimum for those with positive roots. Ranking of absolute values of latent roots corresponds to ranking of variables for relative importance.

RESULTS AND DISCUSSION

Because results obtained doubtless are unique to the specific climate involved, means of the climate measures are presented by month for the period studied (Table 1). Additional descriptions of the climate and herd management factors have been published (23, 24). Climatic variables such as maximum temperature, minimum relative humidity, and solar radiation were fitted individually to determine general trends and reductions in error sums of squares (23, 24). Prediction equations were developed for individual climatic variables. These 102 prediction equations (2 breeds, 3 climate measures, 17 response variables) are not presented here due to lack of space but can be obtained from the senior author. Means for response variables are in Table 2 for the five responses described in detail in this paper. In these preliminary analyses (models including no interactions between climatic variables), effects of maximum tem-

TABLE 1. Characteristics of climate, Gainesville, FL.[1]

	Maximum temperature (°C)			Minimum temperature (°C)			% Relative humidity			Solar radiation (Langleys)		
Month	High	Low	Mean	High	Low	Mean	High	Low	Mean	High	Low	Mean
Jan	27.2	9.4	20.0	17.8	−6.1	6.7	93	19	46	425	72	262
Feb	30.0	15.6	23.9	18.9	−2.8	10.0	78	23	44	567	66	431
Mar	32.2	16.7	26.1	18.3	1.1	10.6	56	17	36	647	242	493
Apr	31.1	22.2	27.8	20.6	2.8	12.8	81	20	42	756	204	554
May	34.4	22.8	30.6	22.2	10.6	17.2	60	19	41	752	301	543
Jun	36.1	29.4	32.8	23.3	18.3	20.6	67	33	46	740	193	584
Jul	36.1	30.0	33.3	23.3	20.6	22.2	60	35	46	700	244	537
Aug	35.6	27.2	32.2	23.3	19.4	21.1	85	38	53	706	138	507
Sep	35.6	26.1	31.1	23.9	17.8	20.6	72	38	53	579	190	426
Oct	31.7	22.2	28.9	22.8	2.8	16.1	64	25	43	565	240	426
Nov	28.3	20.0	25.0	18.3	2.2	11.1	71	12	43	495	189	354
Dec	27.8	12.8	21.1	21.1	−2.8	6.7	99	27	52	404	93	269

[1] From (9).

perature below 21°C were slight for most traits but were pronounced as temperatures increased above 27°C. Most yields and percentages declined above 27°C. Chloride content of milk increased steadily with temperature, reflecting the chloride lactose shift that occurs as an animal responds to environmental stress. All yield traits declined as relative humidity increased from 12 to 99%. Yield traits also declined with rising solar radiation. Most reductions due to climate were statistically significant.

During climatic stress, high environmental temperatures and intense solar radiation restrict mobility and feed intake of an animal and result in rapid declines in production. Hot weather indirectly affects milk yield through an increase in body temperature, which causes depression in feed intake (17). This factor could not be evaluated in the present study, because observations on body temperatures were not available. Climatic influences on milk yield were more pronounced in early to mid-lactation than in late lactation (a climate by stage of lactation interaction). This would be expected, because cows during the first trimester of lactation are either in a negative or near negative energy balance, and decreases in energy intake due to low feed intake would reduce milk production. Therefore, cows calving during hot summer months are likely to produce less milk during the lactation (25).

TABLE 2. Mean daily milk yield and composition.[1]

Trait	Holsteins	Jerseys
Milk yield, kg	18.19	11.51
Fat, %	3.35	5.01
Protein, %	3.32	3.80
Protein yield, kg	.58	.43
Reflectance, %[2]	90.40	91.30

[1] Abridges from (24).

[2] Feulgen – DNA reflectance percent.

Response surfaces then were approximated by a second order model with data adjusted by least squares for effects of age of cow, stage of lactation, stage of pregnancy, year, sire, cow and lactation, as listed in the preliminary model. Mathematical model for these RSM analyses thus included 10 terms plus error, the intercept, the linear effects of solar radiation, minimum relative humidity, and maximum temperature (X_1, X_2, and X_3), their quadratics, and the interactions of the linear terms. Results of six response surface analyses are given in detail.

Surface 1: Holstein Milk Yield with Independent Variables Solar Radiation (X_1), Relative Humidity (X_2), and Maximum Temperature (X_3)

From the signs of the latent roots (L_1–L_3) the predicted value of a response variable at the

TABLE 3. Solutions for selected response surface analyses.

Solutions	Holstein milk yield	Jersey milk yield	Holstein fat	Jersey protein	Jersey protein yield	Holstein relfectance
	(kg)	(kg)	(%)	(%)	(kg)	(%)
Stationary points (SP)[1]						
X_1	301.08	276.41	109.15	300.30	487.15	359.21
X_2	33.38	78.17	89.08	16.33	56.39	53.87
X_3	24.68	19.40	30.80	10.57	16.20	26.78
Estimated mean at SP	27.11[2]	11.32	3.50	4.13	.45	97.88
Latent Roots [3]						
L_1	7.53	2.69	.58	.52	2.84	12.93
L_2	420.96	504.57	−123.85	−33.56	222.71	1367.08
L_3	−2506.50	−719.20	219.66	296.00	−5042.30	−6612.59
Latent Roots[3,4]						
L_1	−.66	3.75	−.53	−.52	6.72	43.96
L_2	42.12	−.99	−35.99	−35.99	−737.29	−3788.37

[1] X_1 = Solar radiation (Langleys), X_2 = minimum relative humidity (%), X_3 = maximum temperature (°C).

[2] See text for interpretation of SP.

[3] For corresponding X_1; values coded 10^6.

[4] For X_1 and X_2, with X_3 fixed at its SP.

stationary points of the climate measures was at a minimum for canonical variables X_1 and X_2 and at a maximum for canonical variable X_3 (Table 3). As these canonical variables are linear functions of the original variables, this implies that an increase in temperature would reduce milk yield whereas an increase in solar radiation or relative humidity would increase milk yield. Because $|L_3| > |L_2| > |L_1|$, changes in maximum temperature would have most influence on milk yield followed by changes in relative humidity, followed by solar radiation. Up to a maximum temperature of 24.7°C, an increase in solar radiation from 301 Langleys or an increase in relative humidity at solar radiation below 301 Langleys would cause an increase in milk yield. The shape of the response system was like a saddle. Adjusting the fitted equation to 24.68, SP for X_3, following new values for latent roots were obtained (values for SP remained unchanged): L_1 = -.00000066, L_2 = .00004212. These results suggested two regions for optimum milk production in Holsteins. The first region was at maximum temperature below 24.7°C, solar radiation below 301 Langleys, and minimum relative humidity above 33.4%. The second region was a maximum temperature below 24.7°C, solar radiation above 301 Langleys, and minimum relative humidity below 33.4%.

Surface 2: Jersey Milk Yield

As with Holsteins, the predicted SP for milk yield in Jerseys was for minimum X_1 and X_2 and maximum of X_3. Because the absolute value of L_3 was larger than L_2 and L_1, changes in maximum temperatures affected milk production more than changes in relative humidity and solar radiation, in that order. After adjusting the fitted equation to SP of 19.40 for X_3, the following latent roots were obtained :L_1 = .00000375, L_2 = -;00000099. Results indicated that the SP for Jersey milk yield was 11.3 kg/d. Optimum climatic conditions for Jersey milk production would be at maximum temperature below 19.4°C. As long as temperature remained below 19.4°C, a rise in solar radiation or relative humidity would increase milk yield, The shape of the response system was like a saddle.

By combining results from Holsteins and Jerseys, the optimum climatic conditions for milk production would be at maximum temperature below 19.4°C, minimum relative humidity between 33.4 and 78.2%, and increasing solar radiation. This implied that cool sunny days with moderate humidity provided optimum conditions for milk production in north central Florida. These optimum conditions also should apply to other dairy breeds falling between Holsteins and Jerseys in body size and milk production. It should be noted, however, that very cold temperatures are uncommon in Gainesville, and little environmental protection other than natural shade was provided to the animals. However, there was a considerable range in solar radiation and minimum relative humidity during the study (Table 1).

Surface 3: Holstein Fat Percent

The predicted SP of 3.50% fat was at the maximum X_1 and X_2 and minimum X_3. From the absolute magnitude of the absolute values of latent roots, temperature affected fat percent more than did relative humidity or solar radiation. Relative humidity influenced fat percent more than did solar radiation. After adjusting for X_3 at 30.80, new latent roots were :L_1 = −.00000053, L_2 = −.00001538. Because both L_1 and L_2 were negative, optimum conditions for highest fat percent with Holsteins would be expected at maximum temperatures below 30.8°C, solar radiation below 109 Langleys, and minimum relative humidity below 89.1%. The shape of the response system represented a maximum with a peak at the top corresponding to 3.50% fat. A move in any direction would decrease fat percent. Overall mean fat percent for Holsteins in this study was 3.35% (Table 2).

Surface 4: Jersey Protein Percent

The SP of 4.13 was at the maximums of X_1, X_2, and X_3. Protein percent was affected most by maximum temperature, followed by relative humidity and solar radiation. After adjustment to SP for X_3 of 10.57, new latent roots were −.00000052 and −.00003599. Because both were negative, maximum protein percent would be expected to be 4.13% at 300 Langleys solar radiation, 16.3% relative humidity, and 10.5°C maximum temperature. The response at SP represented the maximum point in the fitted surface and an increase in any of the climatic parameters would reduce protein percent. Mean Jersey protein percent (Table 2) was 3.80%.

Surface 5: Jersey Protein Yield

Again, maximum temperature had the most influence on protein yield, followed by relative humidity, and solar radiation. New latent roots were .00000672 and −.00073729. Because L_2 was negative, the expected response was at maximum relative humidity and minimum solar radiation. The shape of the response system was like a saddle (difference in the signs of latent roots), indicating that optimum conditions for protein yield would be at maximum temperature below 16.2°C, relative humidity below 56.4%, and solar radiation above 487 Langleys, (i.e., cool dry sunny days).

Surface 6: Holstein Feulgan – DNA Reflectance Percent

The estimated response was at maximum X_1 and X_2 and minimum X_3. Maximum temperature had the greatest influence on DNA reflectance (REF), followed by relative humidity and solar radiation. New latent roots were .00004396 and −.00378837. The SP was at the minimum X_1 and maximum value X_2. Shape of the response system was like a saddle as with Jersey protein yield. As long as minimum relative humidity was at least 53.9% and maximum temperature was below 26.8°C, a rise in solar radiation values from 359 Langleys was associated with decreased REF.

DISCUSSION

Results to characterize effects of climate on milk production are important for commercial milk production, perhaps particularly under circumstances where climate is a limiting factor. Although data used in this study were from one farm representing a unique environment, results regarding interplay of climatic parameters with physiological responses of dairy animals should still be applicable under different situations.

Results of RSM analyses may or may not confirm results of analyses using mathematical models that do not include interactions. Hence, no real conflict exists between our preliminary analyses and the RSM analyses. For example, in models without interactions, increasing temperature, minimum relative humidity, and solar radiation, each was associated individually with declines in milk yield. Because interactions were present, their inclusion in the model leads to an improved interpretation of the data.

To our knowledge, this was the first study in which RSM was used to obtain optimum climatic conditions for milk production (12). The technique is useful in other areas of animal production where the objective is to find an optimum response. However, a specific limitation of the RSM is that it may not always provide the values that lie in the experimental region. Mead and Pike (20) elaborated the advantages and disadvantages of using a quadratic response function of the type used in our study. The advantage of such a function is a well-defined optimum value that can easily be obtained by least squares. The major disadvantage is the unreliability of extrapolation outside the range of independent values that may lead to impossible predicted values.

The existence of SP and predicted response in some cases may complicate interpretation of results. This is likely to happen for highly variable traits. The RSM will always locate the SP within the experimental region if the response surface can be adequately approximated by an n^{th} order model and if the SP is within the experimental region. Therefore, for highly variable traits, use of a third degree response model rather than the second degree used in this study could be helpful. Another modification could be to put constraints on ranges of variables. This would be analogous to a linear programming problem with the objective of optimization of a multiple variable function subject to multiple inequality constraints. A Lagrangian multiplier approach may be used to solve this problem so that if solutions are obtained, they would fall within the normal specified region.

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