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Novel heat index models for subtropical region based on daily milk production in crossbred Holstein cows

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Abstract: The quantification of the effect of heat stress imposed due to higher rate of heat gain on animal production is a prerequisite while estimating effects of heat stress. Temperature humidity index (THI) models developed empirically using meteorological parameters have been utilized as an indicator of heat stress. This study attempted to develop a heat index model with respect to productivity of the crossbred Holstein cows. More than 1.23 million daily milk yield records of 1860 crossbred cattle spread over a duration of 30 years were utilized. Statistically significant ($p < 0.0001$) partial regression coefficients were estimated as 0.0748 ± 0.0009 for dry bulb temperature (T_{db}) and –0.2228 ± 0.0011 for wet bulb temperature in model 1, –0.0182 ± 0.0005 T_{db} and –0.1205 ±0.0006 for vapour pressure in model 2, –0.0150 ± 0.0006 for T_{db} and –0.1151 ± 0.0006 for dew point temperature in model 3 while as –0.1283 ± 0.0004 for T_{db} and –0.0394 ± 0.0002 for relative humidity in model 4. The ratio of the partial regression coefficients of meteorological parameters ($\beta 2/\beta 1$) was –2.9791 in model 1, 6.8739 in model 2, 7.6731 in model 3 and 0.3073 in model 4. The developed THI models are based on the effect of meteorological parameters on daily productivity of the dairy animals, so the weightages to meteorological parameters were contrastingly different than the reported THI models. These models may successfully be used to evaluate the impact of heat stress on crossbred Holstein cows with respect to milk productivity and many other traits.

Key words: Temperature humidity index, cattle, heat stress, daily milk yield

1. Introduction

A thermoregulatory mechanism exists in homoeothermic animals as they have a narrow range of body temperature for optimal biological functionality. However, thermoregulatory mechanism is an active process that requires energy, and it has limitations to functionality. A higher rate of heat gain coupled with low rate of heat dissipation imposes a certain stress on organisms, called as heat stress. The quantification of the heat stress imposed on the animals by environment is a major step in estimating effects of heat stress. Earlier studies were based on daily maximum temperature or on average daily temperature. Temperature humidity index (THI) is a single indicator combining effects of temperature and humidity together to measure heat load. THI is a determinant of meteorological impact derived through combination of ambient temperature and relative humidity under a shaded area as it determines the extent of heat gain and heat loss. The THI could be effectively used to determine the influence of heat stress on productivity of dairy cows. Various THI models have long been used for assessing the impact of environmental stressors particularly ambient temperature and humidity on humans and animals. However, many of such models have been devised empirically and further validation based on either human opinions on discomfort or on physiological changes in humans or animals like sweating, panting, hyperthermia etc.

Meteorological parameters like ambient temperature (T_{db}), wet bulb temperature (T_{wb}), maximum temperature (T_{max}), minimum temperature (T_{min}), dew point temperature (T_{dp}), relative humidity (RH), vapour pressure (VP) etc. have been utilized in various models to calculate THI values. THI models developed by Thom [1] and Bianca [2] (THI_1, THI_2 and THI_3 in Table 1) used only T_{db} and T_{wb} for heat load estimation. National Research Council, USA [3] adapted three different formulae (THI_4, THI_5, and THI_6 in Table 1) that used T_{db} and T_{wb}, T_{db} and T_{dp}, and T_{db} and RH, respectively. The THI_7 model given

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Table 1. Different THI models.

SN	THI Model	Reference
1.	$THI_1 = [(0.4 \times (T_{db} + T_{wb})) \times 1.8 + 32] + 15$	[1]
2.	$THI_2 = (0.35\ T_{db} + 0.65\ T_{wb}) \times 1.8 + 32$	[2]
3.	$THI_3 = (0.15\ T_{db} + 0.85 \times T_{wb}) \times 1.8 + 32$	[2]
4.	$THI_4 = (T_{db} + T_{wb}) \times 0.72 + 40.6$	[3]
5.	$THI_5 = [(0.55\ T_{db} + 0.2\ T_{dp}) \times 1.8 + 32] + 17.5$	[3]
6.	$THI_6 = (1.8\ T_{db} + 32) - (0.55 - 0.0055\ RH) \times (1.8\ T_{db} - 26.8)$	[3]
7.	$THI_7 = 1.8\ T_{db} + 32 - 0.55\ (1 - RH)\ (1.8\ T_{db} - 26)$	[4]
8.	$THI_8 = T_{db} + 0.36\ T_{dp} + 41.2$	[5]
9.	$THI_9 = 0.8\ T_{db} + [(RH/100) \times (T_{db} - 14.4)] + 46.4$	[6]
10.	$THI_{10} = T_{db} - [(0.31 - 0.31 \times RH/100)\ (T_{db} - 14.4)]$	[7]

T_{db}: Dry bulb temperature, T_{wb}: Wet bulb temperature, T_{dp}: Dew point temperature, RH: Relative humidity.

by National Oceanic and Atmospheric Administration (NOAA) [4] uses daily T_{max} and RH. The THI_8 model developed by Yousef [5] utilized a combination of T_{db} and T_{dp}, while THI_9 model given by Mader et al. [6] and THI_{10} model given by Marai et al. [7] uses RH along-with T_{db}.

An increase in global-mean temperature by 1.4 °C to 3 °C till 2050 has been predicted [8]. With such climatic change, the productivity of current livestock is bound to be adversely affected. Further, some estimates anticipate that approximately double food productivity will be needed by 2050 [9] and more than two-thirds of global population will not have enough land to produce the food for an affluent diet by 2050 [10]. The availability of the natural resources and crops lead to limit the number of livestock that can be sustained without competing with humans for nutritional requirements that will require rearing animals with high productivity. The sensitivity of milk yield to heat stress is established and quantified in cattle by many workers. An increase in THI value from 76 to 82 lead to higher milk yield depression in higher producers than moderate to low milk producing cows [11]. Hossein-Zadeh and co-workers [12] reported that in THI range of 81–90 cows had lower milk and fat yields than lower THI groups. Further an analysis of test day milk yield of Holstein cattle indicated a significant decrease of 0.12 kg for unit increase of THI above 74 under the current managerial practices [13]. However, even if value of THI (ranging from 47.08 to 70.13) didn't exceed the critical comfort level of 72, still amount of milk decreased for each unit of increase in the value of the THI [14].

The heat tolerance traits among the animals show genetic variability so selection of animals to improve thermo-tolerance is possible. The selection for improving thermo-tolerance in animals, however, can be more accurate with the help of a THI value that is formulated for the specific purpose. Further, A THI model explicitly designed on crossbred cattle may be suited for estimation of heat stress on both exotic (HF) and indigenous (Zebu) cattle along with crossbred herds of dairy importance. Daily milk yield makes a suitable basis for such study due to its ease of recording and sensitivity to heat balance. In current scenario of global climatic changes and increasing demands of animal products for nutritional security of ever growing population, the need of the day is a new THI, better addressing effects of ambient temperature and humidity on productivity of the animals in a more particular way.

2. Material and methods

For the current study daily milk yield records of pedigreed Karan Fries cattle (crossbred of Holstein Fresian bulls with Tharparkar cows, with most of the animals having 50% to 62.5% exotic inheritance), spread over a duration of 30 years from January 1984 to December 2013 were utilized. Animals with less than 100 days of lactation records or less than 500 kg milk yield and animals involved in experiments were excluded from the study. Only 305 days daily milk yield (dMY) records from first to fourth parity of the animals were utilized for analysis.

The climatological records from meterological station near dairy farm were collected for 30 years period of study (1984 to 2013) on the parameters T_{db} in °C, T_{wb} in °C, VP in mm Hg, T_{dp} in °C and RH in percentage. The geographical location of ICAR-National Dairy Research Institute, Karnal, India is at coordinates 29°42′13″N latitude and 76°58′44″E longitude situated at an altitude of 250 m above the mean sea level. The distance between dairy farm and metrological observatory is about 2.9 km.

The location of the dairy farm comes under the Trans Gangetic plains region and has been classified as Subtropical steppe (BSh) in Koppen & Geiger climate classification. The average annual rain fall is approximately between 760 mm and 960 mm. Temperature varies greatly in this area with a minimum of –0.2 °C to the maximum of 47.0 °C during the study period (1984 to 2013). Average dry bulb temperature varied from 5.70 °C to 39.70°C with coefficient of variation as 29.535%; whereas, average wet bulb temperature varied from 4.20 °C to 29.50 °C with coefficient of variation of 31.226% and average relative humidity ranged from 12.00% to 100.00% during thirty years (table 2).

After normalization and standardization of the records, 1236381 dMY records for 4492 lactations of 1860 crossbred cattle was considered for modeling. dMY records of crossbred cattle were used as dependent variables with the regression of dry bulb temperature, an indicator of humidy and fixed effects of other factor(s) using following mixed model in SAS software version 9.3:

$$Y_{ijklm} = \mu + \beta_1 T_{1i} + \beta_2 T_{2i} + A_j + G_k + P_l + pa_m + AG_n + LS_o + e_{ijklmnop}$$

where,

$Y_{ijklmnop}$ = pth dMY of the oth stage of lactation of mth parity of jth animal in nth age group, kth genetic group and lth period

μ = overall mean

β_1,β_2 = partial regression coefficients

T_{1i}, T_{2i} = meterological parameters of the ith day

A_j = random effects of jth animal

G_k = fixed effects of kth genetic group (level of exotic inheritance)

P_l= fixed effects of lth period of calving (1 to 10, 3 years each)

Pa_m = fixed effects of mth parity (1 to 4)

AG_n = fixed effects of nth age group at first calving (1 to 3, mean AFC±SD)

LS_o = fixed effects of oth stage of lactation (1 to 10, 30 days each)

$e_{ijklmnop}$ = random error ~ NID (0, σ^2_e)

The above mentioned model was fitted for dry bulb temperature with combination to wet bulb temperature, dew point temperature, vapour pressure, and relative humidity one by one. The ratio of the regression coefficients for two metrological parameters (β_2/β_1) was calculated for each of the four models and the partial regression coefficients obtained from the above model were empirically adjusted while maintaining the ratio between the two meteorological parameters fitted in the model. A constant was empirically fitted in the model such that the index value of all the models remains within the conventional range of THI models with similar average index values.

3. Results and discussion

The dMY data was analysed for the effects of animal, genetic group, stage of lactation, age group, parity, and period alongwith four different combinations of meteorological indicators of temperature and humidity with an aim to derive adjusted regression coefficients for meteorological parameters, as a base of new THI model.

3.1 Regression modeling

The effects of animal, genetic group, period, parity, age at first calving and stage of lactation were found as significant ($p < 0.0001$) in all the models (Table 3) fitting different

Table 2. Descriptive statistics for metrological parameters.

Parameters	T_{min}	T_{max}	T_{db}	T_{wb}	VP	T_{dp}	RH
Mean	17.04	29.97	24.48	19.40	14.95	16.04	65.62
Standard error	0.07	0.07	0.07	0.06	0.06	0.07	0.16
Median	17.40	31.20	26.10	19.70	12.80	14.86	68.00
Standard deviation	7.75	6.98	7.23	6.05	6.42	6.94	16.27
Coefficient of variation	45.49	23.28	29.52	31.21	42.94	43.24	24.80
Kurtosis	–1.32	–0.45	–1.01	–1.20	–1.23	–1.19	–0.10
Skewness	–0.18	–0.32	–0.32	–0.23	0.45	0.06	–0.56
Range	32.20	39.40	34.00	25.30	26.60	38.19	88.00
Minimum	–0.20	7.60	5.70	4.20	3.70	–9.61	12.00
Maximum	32.00	47.00	39.70	29.50	30.30	28.58	100.00

T_{min}: Minimum temperature, T_{max}: Maximum temperature, T_{db}: Dry bulb temperature, T_{wb}: Wet bulb temperature, VP: Vapor pressure, T_{dp}: Dew point temperature, RH: Relative humidity.

Table 3. ANOVA table for general linear model with different metrological parameters for changes in daily milk yield.

Source	DF	Model 1		Model 2		Model 3		Model 4	
		Mean square	F value	Mean square	F value	Mean square	F value	Mean square	F value
Animal	1877	3849.43	389.32*	3849.77	389.65*	3850.72	388.38*	3849.93	389.15*
Genetic group	2	4096.80	414.34*	4092.40	414.20*	4042.30	407.70*	4087.37	413.15*
Age at first calving	2	4892.19	494.78*	4894.02	495.34*	4858.99	490.07*	4824.30	487.64*
Period of calving	9	12512.50	1265.47*	12503.46	1265.51*	12536.00	1264.36*	12528.42	1266.38*
Parity	3	48430.64	4898.11*	47921.37	4850.27*	48449.43	4886.54*	49029.67	4955.93*
Stage of lactation	9	509853.39	51564.90*	509692.53	51587.50*	510852.63	51523.80*	510246.31	51575.80*
Dry bulb temperature	1	68439.37	6921.73*	11311.04	1144.82*	7074.67	713.54*	816853.80	82567.80*
Wet bulb temperature	1	426938.35	43179.10*	-	-	-	-	-	-
Vapour pressure	1	-	-	436150.19	44144.10*	-	-	-	-
Dew point temperature	1	-	-	-	-	393280.91	39665.70*	-	-
Relative humidity	1	-	-	-	-	-	-	420124.47	42466.30*

F values with * mark are significant ($p < 0.0001$).

meteorological parameters. The partial regression coefficients (β_1 and β_2) for T_{db} and T_{wb} in model 1, T_{db} and VP in model 2, T_{db} and T_{dp} in model 3 and T_{db} and RH in model 4 revealed a significant linear association with daily milk yields with model efficiency parameters (table 3). Statistically significant ($p < 0.0001$) partial regression coefficients were estimated as 0.0748 ± 0.0009 and –0.2228 ± 0.0011, respectively for T_{db} and T_{wb} in model 1, as –0.0182 ± 0.0005 and –0.1205 ± 0.0006, respectively for T_{db} and VP in model 2, as –0.0150 ± 0.0006 and –0.1151 ± 0.0006, respectively for T_{db} and T_{dp} in model 3 while as –0.1283 ± 0.0004 and –0.0394 ± 0.0002, respectively for T_{db} and RH in model 4. The ratio of the partial regression coefficients (β_2/β_1) was –2.9791 for T_{db} and T_{wb} in model 1, 6.8739 for T_{db} and VP in model 2, 7.6731 for T_{db} and T_{dp} in model 3 and 0.3073 for T_{db} and RH in model 4. The most contrasting weightages were found in model 1 where partial regression coefficient for T_{db} was positive and the whole reduction in daily milk yield was being explained by T_{wb} where, as in model 2 through 4, both the metrological parameters explained decline in the daily milk yield, however, with different weightages. The ratio of regression coefficients was highest in model 3 with T_{dp} and lowest in model 4 with RH.

The model efficiency parameters for the four models were comparable with the coefficient of determination (R^2 value) ranging from 0.5552 for model 2 to 0.5536 for model 3. The lowest AIC, AICC, and BIC values were estimated for model 2, followed by model 1, model 4 and highest in model 3 (Table 4) denoting a marginal superiority of model 2 over the rest of the models whilst model 4 was inferior most with respect to the model efficiency parameters.

3.2 Construction of heat index models

The ratio of regression coefficients was maintained while transforming the regression equations to THI models by giving appropriate weightage. The intercepts were adjusted to get the average THI value with each model to be equal. The THI models developed using T_{db} and T_{wb} in model 1, T_{db} and VP in model 2, T_{db} and T_{dp} in model 3 and T_{db} and RH in model 4 were consequently named as THI_w, THI_v, THI_d and THI_h, respectively, the equations for which has been represented in Table 5. THI values calculated from the developed THI models showed slightly platykurtic and almost symmetrical distribution (Table 6). The minimum value of average daily THI was observed in THI_d (37.04) while maximum value of average daily THI was observed in THI_v (95.11). The coefficient of variation was lower in THI_v (14.37) and THI_h (14.48) as compared to THI_w (16.26) and THI_d (17.06).

The difference in weightage to ambient temperature and humidity is highlighted by the fact that indices with larger weights on humidity to be more suitable for humid climates and where humidity does not reach levels that could compromise evaporative cooling, indices with the most emphasis on ambient temperature are preferable [15]. There was a large variation among THI models for weightage to ambient temperature and humidity, such as the THI model by Thom [1], and a slightly modified THI adopted by NRC [3] shown as THI_1 and THI_4 in Table 1 gives equal weightage to dry and wet bulb temperatures;

Table 4. Efficiency parameters for model with different metrological parameters for changes in daily milk yield.

Parameters	Model 1	Model 2	Model 3	Model 4
RMSE	3.145	3.143	3.149	3.145
Dependent mean	12.306	12.306	12.306	12.306
R-Square	0.555	0.555	0.554	0.555
Adjusted R-square	0.554	0.555	0.553	0.554
AIC	4071089	4070156	4074494	4071779
AICC	4071095	4070162	4074500	4071785
BIC	2834743	2833810	2838148	2835433
SBC	2857648	2856715	2861053	2858338
ASE	9.872	9.865	9.900	9.878

RMSE: Root mean square error, AIC: Akike information criterion, AICC: AIC with a correction for small sample sizes, BIC: Sawa Baysian information criterion, SBC: Schwarz Bayesian information criterion, ASE: Average square error.

Table 5. Equations for developed THI models.

Sr. no.	THI model	Metrological parameters		Equation
		temperature	humidity	
01	THI_w	T_{db}	T_{wb}	$THI_w = 38.717 + 2.979 \times T_{wb} - T_{db}$
02	THI_v	T_{db}	VP	$THI_v = 45.280 + 0.21 \times T_{db} + 1.444 \times VP$
03	THI_d	T_{db}	T_{dp}	$THI_d = 41.022 + 0.21 \times T_{db} + 1.611 \times T_{dp}$
04	THI_h	T_{db}	RH	$THI_h = 38.717 + 1.5 \times T_{db} + 0.461 \times RH$

T_{db}: Dry bulb temperature, T_{wb}: Wet bulb temperature, VP: Vapor pressure, T_{dp}: Dew point temperature, RH: Relative humidity.

two THI models proposed by Bianca give more weightage to wet bulb temperature as the weightage ratio of T_{db} and T_{wb} (W_1/W_2) is 0.538 and 0.176, respectively in THI_2 and THI_3 [2]. However, none of previous models found negative weight to any component as it was seen in the proposed THI_w model.

THI models with dew point temperatures as their component proposed by Yousef [5] and adapted by NRC [3] give more weightage to dry bulb temperature and maintain near similar weightage ratio of T_{db} and T_{dp} as 2.778 and 2.750, respectively while the developed THI_d model gave more weightage to T_{dp} as evident by weightage ratio of 0.130. Further, the reported models incorporating RH give negative weightage to (1-RH)×T_{db} component as seen in models adapted by NRC [3], NOAA [4], reported by Marai et al. [7] and Mader et al. [6]. The THI model developed for Egypt gives positive weightage to both temperature and RH [13]. This was in contrast to the developed model THI_h that gives positive weight to RH alone.

Comparative higher weightages to humidity in all four developed THI models indicate more influence of humidity as compared to other reported THI models. This makes developed THI models to be appropriate for regions with moderate to high temperature accompanied by high humidity variations. The attempts made in this study warrant an adjustment to the known THI models to make them better suited for explaining the phenomenon of heat stress among the animals.

4. Conclusion

Many THI indices were reported till date that have been used for biological studies to determine the impact of climatological stress on biological systems. The basis of their development was either empirical derivation or physiological parameters of animals and humans.

Table 6. Parameters and descriptive statistics for developed heat index models.

Parameters	THI_w	THI_v	THI_d	THI_h
Intercept	38.717	45.280	41.022	5.050
W_1	–1.000	0.210	0.210	1.500
W_2	2.979	1.444	1.611	0.461
W_1/W_2	– 0.336	0.145	0.130	3.254
Mean	72.00	72.00	72.00	72.00
Standard error	0.11	0.10	0.12	0.10
Median	69.91	69.19	70.37	70.64
Standard deviation	11.96	10.34	12.28	10.42
Coefficient of variation	16.62	14.37	17.06	14.48
Kurtosis	–1.22	–1.27	–1.22	–1.09
Skewness	0.11	0.33	0.00	0.02
Range	51.47	42.36	56.99	50.60
Minimum	43.13	52.76	37.04	41.22
Maximum	94.60	95.11	94.03	91.82

The developed heat indices were contrastingly based on the effect of climatological parameters on daily milk productivity of the crossbred Holstein cows, which may address the concern of evaluating the climatological stress on cattle with respect to any physiological aspects affected by heat stress including production, reproduction, and many more.

Conflict of interest

The authors declare that there is no conflict of interest whatsoever related to the present study.

Ethical approval

The ethical approval was not required as the study was conducted on previously recorded data, and no handling or experimentation on the animals was carried out.

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