



Methods for detecting heat stress in hutch-housed dairy calves in a continental climate

B. Dado-Senn,¹ V. Ouellet,² V. Lantigua,³ J. Van Os,¹ and J. Laporta^{1*}

¹Department of Animal and Dairy Sciences, University of Wisconsin-Madison, Madison 53706

²Department of Animal Sciences, Université Laval, Québec City, Québec, G1V 0A6 Canada

³Department of Animal Sciences, University of Florida, Gainesville 32611

ABSTRACT

Dairy calves exposed to solar radiation, elevated ambient temperature, and humidity are at risk of impaired welfare and productivity. Initial detection of thermal discomfort requires determination of optimal heat stress indicators and thresholds. Such values have recently been established in calves in chronic, subtropical, and acute continental environments but not in continuous, temperate conditions. Herein, the objectives were to determine associations between animal-based and environmental heat stress indicators and establish environmental breakpoints for hutch-raised dairy calves during a continental summer. From June to August, dairy calves ($n = 63$; 14 to 42 d of age) were individually hutch-housed and managed according to the dairy standard operating procedures in Arlington, Wisconsin. Calf respiration rates (RR), rectal temperatures (RT), shaved or unshaved skin temperatures (ST), and hutch internal and external air speed were measured thrice weekly at 0700 and 1400 h after a 15 min hutch restriction. Environmental indices including dry bulb temperature (T_{db}), black globe temperature, and relative humidity were measured every 15 min, averaged hourly, and used to calculate temperature-humidity index (THI) using 8 different equations (THI_{1-8}). Correlation and linear regression models were used to determine relationships within and between animal-based and environmental indicators. Environmental breakpoints were established using segmented regression models to estimate THI and T_{db} thresholds for abrupt changes in animal responses. There were strong, positive correlations between animal-based indicators and T_{db} or THI_{1-8} , with the strongest association observed between unshaved ST and T_{db} ($r = 0.80$). The linear regression of animal-based indicators with the best fit included T_{db} or T_{db} plus relative humidity and air speed. The threshold at which RR and RT began

to rise was at a THI of 69 for both or at a T_{db} of 21.0 or 21.5°C, respectively. No threshold was established for ST. Together, these outcomes indicate that T_{db} is an appropriate measurement to detect thermal discomfort for calves in a temperate summer climate and individual hutch housing. Monitoring of calves is warranted before ambient temperature reaches 21.0°C, corresponding to RR of 40 breaths per minute and RT of 38.5°C, to promote calf comfort and reduce the risk of hyperthermia-related welfare and productivity consequences.

Key words: thermal discomfort, temperature, breakpoint, heifers

INTRODUCTION

Under elevated ambient temperatures, dairy calves experience increased physiological thermoregulatory responses, reduced feed intake, impaired growth, and altered behavior (Roland et al., 2016; López et al., 2018; Dado-Senn et al., 2022). However, most research assessing calf heat stress response has been conducted in subtropical, temperate, wet, hot, or arid climates (i.e., Southeastern and Southwestern United States), as determined by the Köppen-Geiger climate classification (Beck et al., 2018). Assessment of dairy cattle heat stress in cooler, continental climates (i.e., Midwestern and Northeastern United States, southern Canada, or central Europe) is necessary and relevant, as summer temperatures can well exceed the calf thermoneutral zone (Van Iae et al., 2014) and the regional climate temperatures are predicted to increase by at least 1.5°C in the next 50 to 80 years (Beck et al., 2018; IPCC, 2022).

Heat stress indicators can be classified as animal-based or environmental with optimal indicators depending on the climate of interest (Galán et al., 2018; Hoffmann et al., 2019). For group-housed Holstein dairy calves exposed to chronic elevated ambient temperatures in a subtropical environment, we established that skin temperature (ST) and temperature-humidity index (THI) are optimal animal-based and environmental indicators

Received April 28, 2022.

Accepted September 21, 2022.

*Corresponding author: jlaporta@wisc.edu

Table 1. Description of 8 temperature-humidity index (THI) equations used to assess environment for dairy cattle

Name	Equation ¹	Citation
THI ₁	$(1.8 \times T_{db} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26)]$	NRC, 1971
THI ₂	$T_{db} + 0.36 \times T_{dp} + 41.2$	Yousef, 1985
THI ₃	$(0.35 \times T_{db} + 0.65 \times T_{wb}) \times 1.8 + 32$	Bianca, 1962
THI ₄	$(0.55 \times T_{db} + 0.2 \times T_{dp}) \times 1.8 + 32 + 17.5$	NRC, 1971
THI ₅	$(0.15 \times T_{db} + 0.85 \times T_{wb}) \times 1.8 + 32$	Bianca, 1962
THI ₆	$[0.4 \times (T_{db} + T_{wb})] \times 1.8 + 32 + 15$	Thom, 1959
THI ₇	$(T_{db} + T_{wb}) \times 0.72 + 40.6$	NRC, 1971
THI ₈	$(0.8 \times T_{db}) + [(RH/100) \times (T_{db} - 14.4)] + 46.4$	Mader et al., 2006

¹ T_{db} = dry bulb temperature, °C; RH = relative humidity, %; T_{dp} = dew point temperature, °C; T_{wb} = wet bulb temperature, °C.

of heat stress (Dado-Senn et al., 2020). In that study, we further characterized THI breakpoints of 65, 67, and 82, at which respiration rate (**RR**), rectal temperature (**RT**), and DMI, respectively, begin to change (Dado-Senn et al., 2020).

Notably, there are several THI equations with different weights of dry bulb temperature (**T_{db}**) or relative humidity (**RH**; Table 1). Although these THI equations are highly correlated in subtropical lactating dairy cows (Dikmen and Hansen, 2009), their relevance may differ with climate and the physiological state of the animal (i.e., calves). Using a decrease in milk yield as an indicator of heat stress, Bohmanova et al. (2007) reported that THI calculated with larger weight on T_{db} was more suitable to detect heat stress in dry climates, and the THI calculated with larger weight on RH is more suitable in humid climates. Currently, the equation proposed by NRC (1971; THI₁) is the most reported in studies of dairy cattle in various climates and physiological state, while the others are less frequently estimated.

It is unknown whether previously established heat stress thresholds and THI equations translate well for calves in a continental climate or in individual housing situations. Calf hutch systems account for approximately 63% of all calf housing in the United States with 25% indoor and 38% outdoor (NAHMS, 2016). Limited heat stress studies in dairy calves emphasize outdoor calf hutch design or supplemental shade in subtropical or arid regions (Coleman et al., 1996; Carter et al., 2014; Manriquez et al., 2018). A study series recently established optimal indicators and thresholds in hutch-housed Holstein calves in a European continental climate, estimating THI thresholds between 78 and 88, at which animal-based indicators began to rise (Kovács et al., 2018, 2020). While this study was relatively short in duration and captured a much higher THI range, it suggests that calves have a higher threshold for heat stress in a continental environment that is characterized by more acute bouts of heat stress and varied

ambient temperatures both seasonally and diurnally. Establishing environmental breakpoints in dairy calves across a wider range of ambient temperature and THI can serve as a basis to detect initial signs of thermal discomfort and heat stress and subsequently provide proper management interventions tailored to individually housed calves in temperate regions.

The objective of the present study was to establish associations between and thresholds for environmental and animal-based indicators of heat stress in Holstein dairy calves individually hutch-raised across a continental climate summer. A secondary objective was to determine the optimal THI equation for use in dairy calves in a continental climate. These objectives were accomplished through assessing correlations between dairy calf animal-based (i.e., RR, RT, and ST) and environmental indicators [i.e., T_{db} , black globe temperature (**T_{bg}**), air speed (**AS**), RH, and multiple THI equations], equating goodness of fit, and establishing environmental breakpoints at which physiological variables begin to rise or decline in hutch-housed dairy calves from June to August in Wisconsin. We hypothesized that animal-based indicators, particularly ST, would be strongly correlated with T_{db} and THI and that environmental breakpoints would be higher than those previously established for subtropical, group-housed calves due to the greater temporal variation in ambient environment.

MATERIALS AND METHODS

Animals and Experimental Design

This experiment was conducted at the University of Wisconsin-Madison Arlington Research Station from June 14 to August 16, 2021 (i.e., 9 wk) to keep observations within peak summer temperatures. All procedures were approved by University of Wisconsin-Madison Institutional Animal Care and Use Committee (Study #A006455).

Female Holstein dairy calves ($n = 63$) were individually housed in sand-bedded polyethylene calf hutches (Calf-Tel, L. T. Hampel Corp.; $2.1 \times 1.2 \times 1.4$ m; length \times width \times height) with rear-hutch ventilation. Beyond shade provided by calf hutch and rear ventilation, no additional heat stress abatement was provided. All calves had free access to a wired enclosed exercise pen (1.7×1.4 m). Calves were weighed at birth, fed 3.78 L of colostrum, and then managed according to the standard operating procedures of the Blaine Research Dairy. The feeding program consisted of 2 meals of 4 L pasteurized milk and ad libitum grain and water.

The calves in the present study were enrolled on a rolling basis, starting at 14 d and finishing at 42 d of age (i.e., after peak scours incidence but before the initiation of the step-down weaning program) and observed thrice weekly at 0700 and 1300 h. Calves exhibiting signs of scours such as diarrhea, lethargy, or dehydration ($n = 5$) were excluded from measurements until the event passed, as determined by trained research personnel. Due to rolling enrollments during the 9-wk study period, subsets of calves were enrolled later than 14 d of age or unenrolled before reaching 42 d of age, reducing their individual observation numbers and leading to $n = 964$ total observations in the present study.

Environmental Measures

Environmental measurements were recorded every 15 min and averaged hourly using HOBO Pro Series Temp Probes (Onset Computer Corp.) affixed to external structures near the hutch housing. Two HOBO-U12 data loggers recorded T_{db} ($^{\circ}\text{C}$), RH (%), and dew point temperature (T_{dp} , $^{\circ}\text{C}$), and a HOBO Water Temp Pro V2 data logger captured T_{bg} ($^{\circ}\text{C}$). Wet bulb temperature (T_{wb} , $^{\circ}\text{C}$) was determined according to Dikmen and Hansen (2009). From these values, a series of 8 different THI equations were calculated (Table 1).

Air speed (m/s), both hutch external (AS_{ext}) and internal (AS_{int}), was assessed at the same time as animal measures at 0700 and 1300 h thrice weekly, using an anemometer (MS6252A Digital Anemometer System, Proster) hand-held at calf level (0.9 m high) and rotated manually for 10 s to detect maximum AS. Environmental indicators were classified as primary (i.e., commonly measured; T_{db} , T_{bg} , THI_1 , RH, and AS) or secondary (i.e., not as commonly measured; T_{dp} , T_{wb} , and all other THI equations).

Animal-Based Measures

Animal physiological measures including RR, RT, and ST were recorded thrice weekly at 0700 and 1300 h.

Calves were restricted using wire paneling within their individual hutch for 15 min before assessing RR (flank movements for $30 \text{ s} \times 2$). Restriction was conducted to standardize calf environment, represent hutch usage, and minimize the impact of solar radiation inflating ST measures. Next, calves were individually released and RT (SharpTemp V Large Animal Digital Thermometer, PBS Animal Health) and ST (Raytek MiniTemp MT6 Infrared Thermometer; Instrumart) were immediately and simultaneously collected under shaded conditions. The ST was read via infrared thermometer at approximately 15 cm distance from an unshaved skin temperature (ST_U) and a 5 cm^2 shaved skin temperature (ST_S) portion of the left rear rump.

Statistical Analyses

Correlation, linear regression, and segmented regression statistical models were employed to estimate optimal heat stress indicators and environmental thresholds for significant changes in dairy calf physiological responses, similar to Dado-Senn et al. (2020). Daily, hourly, and experimental environmental indicator averages were determined in PROC MEANS in SAS (version 9.4, SAS Institute Inc.) and reported as the mean \pm standard deviation. Pearson correlations based on individual observations were calculated using the CORR procedure to investigate the linear relationship between animal-based and environmental indicators of heat stress. Regression analyses were conducted using PROC MIXED with repeated measures to determine the optimal environmental indicator of heat stress. Here, the best fit model for the regression (i.e., accounting for goodness of fit and complexity) was evaluated using Akaike information criterion (AIC) and pseudo coefficient of determination (R^2), which represents the squared coefficient of correlation between predicted and observed values. All animal-based indicators were consecutively applied as the dependent variable, while combinations of environmental indicators including T_{db} , RH, $AS^{0.5}$, and THI_1 were independent variables. The variable $AS^{0.5}$ was used in place of AS, as it represents the greatest fit for predicting heat flow from AS (Léger and Larochelle, 2006). The model also included the effects of time and age. However, age was not significant and was therefore excluded from the final model. The calf was included as a random effect and the correlation between repeated measures over time was modeled with compound symmetry. A 2-phase segmented regression was conducted with the NLIN procedure to detect significant environmental breakpoints whereby there was an abrupt change in physiological response (i.e., RR, RT, and ST) using the least squares means retrieved from mixed models when T_{db} and THI were

added to the model. The weather data were separated into classes with the first THI class beginning at THI = 60 and the first T_{db} class at 16.2°C. Subsequent classes were set at each 1-point THI and 0.1°C thereafter.

RESULTS

Environmental Outcomes

Hourly, daily, and experimental average external T_{db} , T_{bg} , RH, THI_1 , and AS (experimental means) are reported in Figure 1. There was extensive day-to-day variation for the primary environmental indicators during the experiment (Figure 1A). The average daily ambient environment minimum (T_{db} = 16.3°C; THI = 60.8) occurred on July 8, and maximum (T_{db} = 27.6°C; THI = 77.3) occurred on June 11 for the duration of the experiment. Yet average THI across the experimental period (June to August) was 69.7 (Figure 1C), and of the daily THI_1 averages, 91% remained above a THI of 65, which is a previously established threshold for heat stress indicator in dairy calves in a subtropical climate (Dado-Senn et al., 2020). Further, the average daily T_{db} across the experimental period was 22.6°C (Figure 1C), and of the daily T_{db} averages, only 20% remained above the suggested upper critical temperature of 25°C in the calf thermoneutral zone (Stull and Reynolds, 2008). Daily minimum for T_{db} , T_{bg} , and THI_1 occurred between 0400 and 0500 h and averaged 16.9°C (T_{db}), while daily maximum was between 1500 and 1600 h, which averaged 27.8°C (T_{db}) across the experimental period (Figure 1B). Relative humidity maximum and minimum were the inverse at these times. Hutch external and internal AS were also highly variable but averaged 0.96 m/s and 0.03 m/s, respectively (Figure 1C).

Associations Between Environmental and Animal-Based Indicators

The correlations between animal-based (i.e., RR, RT, ST_S , and ST_U) and primary environmental indicators T_{db} , T_{bg} , and THI_1 were moderate to strong and positive with Pearson correlation coefficients ranging from $r = 0.52$ to 0.80 ($P < 0.0001$, Figures 2A-C and 3A-C). The strongest animal-based versus environmental correlation occurred between T_{db} and ST_U measures ($r = 0.80$), followed by the correlation between T_{bg} or THI_1 versus ST_U ($r = 0.76$ and 0.77 , respectively). The weakest animal-based indicator compared with environmental indicators was RT ($r = 0.52$ to 0.58).

The correlation between animal-based indicators and RH was moderate and negative, with correlation coefficients ranging from $r = -0.40$ to -0.57 ($P < 0.0001$, Figure 2D, 3D). Interestingly, external AS had

a relatively weak, yet still positive and significant, correlation with calf RT ($r = 0.25$) and RR ($r = 0.16$; $P < 0.0001$; Figure 2E). The hutch internal AS was only weakly correlated with RT ($r = 0.07$; $P = 0.05$; Supplemental Table S1; <https://data.mendeley.com/datasets/k63rn3hm6y>; Laporta, 2022), and there were no other significant correlations between the animal-based indicators and AS. Secondary environmental indicator correlations (i.e., T_{wb} and T_{dp}) to animal-based indicators were moderate and positive (Supplemental Table S1).

Similar to reports of T_{db} , T_{bg} , and THI_1 above, correlations between animal-based indicators and all THI were moderate to strong, positive, and significant with Pearson correlations ranging from $r = 0.52$ to 0.78 (Table 2). The strongest associations were found using the THI_2 equation (Yousef, 1985), particularly for ST_U , though the THI_1 , THI_4 , THI_6 , THI_7 , and THI_8 equations were almost as strong and nearly identical ($r = 0.77$ to 0.78). The THI_5 (Bianca, 1962) was the weakest with correlations ranging from $r = 0.52$ for RT to $r = 0.71$ for ST_U .

The associations between these animal-based indicators was determined through Pearson correlations (Table 3). Both RR and ST_U had a moderate, positive correlation to RT at $r = 0.49$, and ST_S was close behind at $r = 0.43$. The ST_S and ST_U had a stronger association to RR at $r = 0.56$ and $r = 0.63$, respectively. Not surprisingly, the strongest correlation was between ST_U and ST_S with $r = 0.80$.

Linear Regression of Environmental Indicators

Table 4 provides the AIC and pseudo R^2 for predicting animal-based indicators RT, RR, ST_S , and ST_U with various environmental measures. The smallest AIC and highest pseudo R^2 (i.e., best fit) for RT was obtained when the model included T_{db} . For all other animal-based indicator equations, the best fit model included T_{db} , RH, and $AS_{ext}^{0.5}$. Yet the models for these indicators containing solely T_{db} or the combination of T_{db} and RH had nearly as good of fit as the full model. In general, the equations with RH or THI_1 as the sole independent variables had some of the highest AIC and lowest pseudo R^2 values, indicating poorer abilities to predict model fit (Table 4).

Temperature-Humidity Index and Dry Bulb Temperature Thresholds

Dry bulb temperature and THI thresholds were established by detecting sudden changes in calf RR and RT (Figure 4). Thresholds were calculated for T_{db} and THI , as T_{db} was the most optimal environmental indicator for outdoor hutch-housed calves in a continental

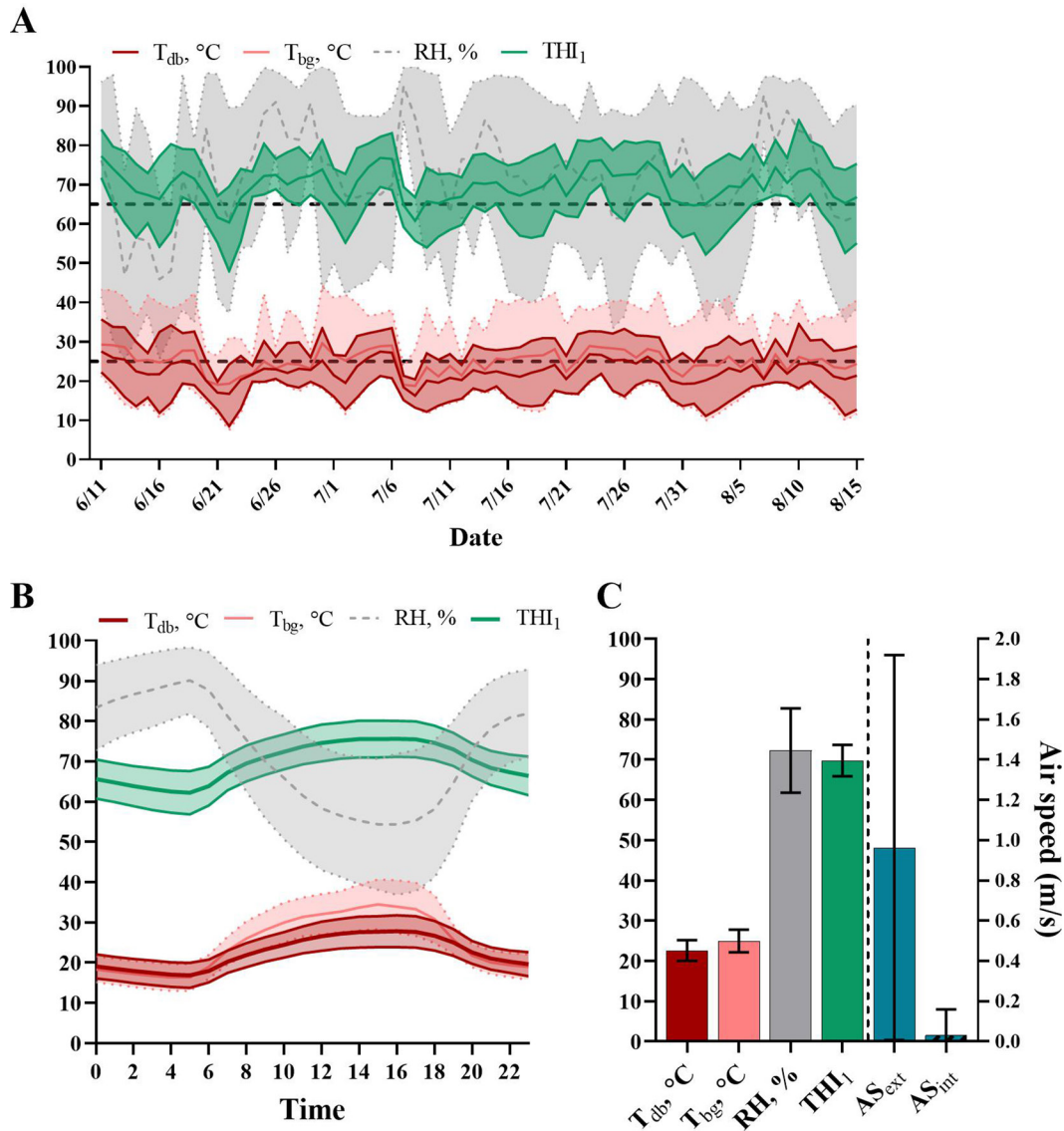


Figure 1. Environmental heat stress indicators during summer in a continental climate. Daily (A) and hourly (B) minimum, maximum, and mean or experimental period mean and standard deviation (C) for dry bulb temperature (T_{db}), black globe temperature (T_{bg}), relative humidity (RH), temperature-humidity index (THI_1 ; THI equation 1; NRC, 1971), external air speed (AS_{ext}), and internal air speed (AS_{int}). Measures, except AS, were recorded every 15 min by external devices near the outdoor hutch-housed calves monitored over the summer (June to August 2021) in a continental climate. Air speed was measured outside the hutch thrice weekly at 0700 and 1300 h. The left y-axis in panels A–C is unitless, as it identifies values for T_{db} (°C, red), T_{bg} (°C, pink), RH (%), and THI_1 (unitless, green). Dotted lines in (A) indicate previously proposed calf thermoneutral zone upper critical temperature (UCT; T_{db}) and THI threshold (Stull and Reynolds, 2008; Dado-Senn et al., 2020).

climate (as reflected by both correlations and goodness of fit), while THI was a commonly selected environmental indicator in other breakpoint studies (Kovács et al., 2020; Dado-Senn et al., 2020). For RR, calves had a T_{db} breakpoint of 21°C and a THI breakpoint of 69, whereby RR began rising above 40 breaths per minute (**bpm**) at a rate of 1 bpm for every unit increase in THI or 2 bpm for every unit increase in T_{db} above the threshold (Figure 4A, B). The respective breakpoints for RT were

21.5°C (T_{db}) and 69 (THI), whereby RT began rising above 38.5°C at a rate of 0.02 or 0.04°C for every unit increase in THI or T_{db} above the threshold, respectively (Figure 4C, D). No breakpoints were detected for ST_U or ST_S within the ambient environment range measured in the present study (i.e., T_{db} = 15 to 35°C or THI = 60 to 90). However, the corresponding ST_U and ST_S values relative to the RR and RT thresholds for T_{db} are 27°C and 32°C, respectively.

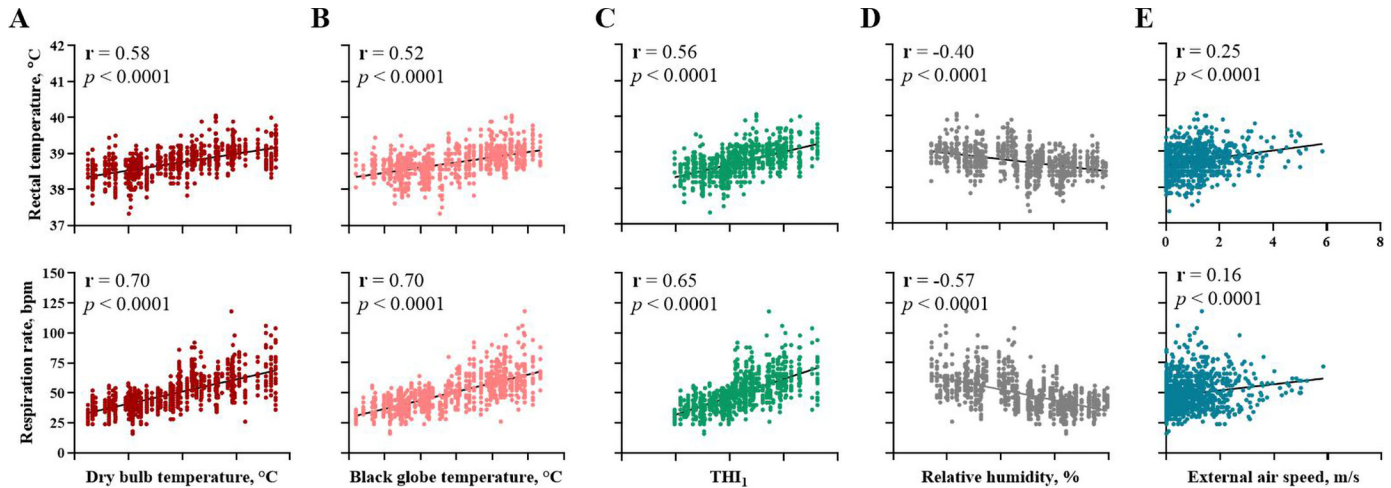


Figure 2. Correlations between environmental and animal-based indicators of heat stress [respiration rate (RR) and rectal temperature (RT)]. Correlations between the animal-based indicators RT and RR versus environmental indicators including dry bulb temperature (A, T_{db} , red), black globe temperature (B, T_{bg} , pink), temperature-humidity index (C; THI_1 , THI equation 1; NRC, 1971, green), relative humidity (D, RH, gray), and external air speed (E, AS_{ext} , blue). Animal-based indicators and AS were recorded thrice weekly at 0700 and 1300 h with the former from outdoor hutch-housed dairy calves monitored over the summer in a continental climate. Other environmental measures were recorded every 15 min near hutches. Lines represent simple linear regression equations; P = significance of the correlation.

DISCUSSION

Elevated ambient temperatures and RH can impair dairy calf productivity and welfare. The negative consequences of heat stress can be exacerbated when calves are housed outdoors in calf hutches, where options for behavioral heat loss are limited (Roland et al., 2016) and calves may be exposed to solar radiation. Therefore, early detection of thermal discomfort using animal-based and environmental indicators in hutch-housed calves is critical for timely implementation of heat abatement. Such indicators and breakpoints are well established and regularly employed to determine heat stress magnitude in adult dairy cows (Galán et al., 2018; Hoffmann et al., 2019) and are becoming more frequently explored in dry cows (Ouellet et al., 2021) and dairy calves. Best indicators and thresholds for

heat stress have been established in subtropical, group-housed calves (Dado-Senn et al., 2020), continental, feedlot beef cattle (Brown-Brandl et al., 2005), and continental, acutely heat-stressed hutch-housed calves (Kovács et al., 2018, 2020). Herein, we determined optimal animal-based and environmental heat stress indicators and breakpoints in hutch-housed dairy calves across a continental summer.

In the present study, there were strong, positive correlations between animal-based indicators and T_{db} and THI_1 , but weak, positive or negative correlations between animal-based indicators and AS_{ext} or RH, respectively. The negative RH correlations are attributed to the drop in RH associated with rising ambient temperatures (Nguyen et al., 2014). The cause of the relationship between external AS and animal responses is less certain but could be related to rising ambient

Table 2. Correlation coefficients between temperature-humidity indices (THI) and animal-based indicators of heat stress¹

Item	THI_1^2	THI_2	THI_3	THI_4	THI_5	THI_6	THI_7	THI_8
RT	0.561	0.574	0.546	0.570	0.519	0.564	0.561	0.561
RR	0.649	0.665	0.614	0.663	0.564	0.645	0.648	0.649
ST_S	0.674	0.681	0.647	0.678	0.604	0.668	0.669	0.674
ST_U	0.774	0.781	0.748	0.781	0.705	0.769	0.773	0.774

¹Correlations between animal-based indicators [i.e., rectal temperature (RT, °C), respiration rate (RR, breaths per minute), and rump skin temperature from a shaved (ST_S , °C) and unshaved (ST_U , °C) area] and the environmental indicator THI (calculated using equations 1–8). Animal-based indicators were recorded thrice weekly at 0700 and 1300 h from outdoor hutch-housed dairy calves monitored over the summer in a continental climate. Temperature-humidity index was calculated from environmental indicators recorded every 15 min near hutches at calf level. $P < 0.001$ for all correlations.

²See Table 1 for THI equation descriptions.

Table 3. Correlation coefficients between animal-based indicators of heat stress¹

Item	RT	RR	ST _s	ST _U
RT				
RR	0.49			
ST _s	0.43	0.56		
ST _U	0.49	0.63	0.80	

¹Correlations between the animal-based indicators [i.e., rectal temperature (RT, °C), respiration rate (RR, breaths per minute), and rump skin temperature from a shaved (ST_s, °C) and unshaved (ST_U, °C) area]. Animal-based indicators were recorded thrice weekly at 0700 and 1300 h from outdoor hutch-housed dairy calves monitored over the summer in a continental climate. $P < 0.001$ for all correlations.

temperature following a bout of cooler temperature that both generates air movement (via air pressure differences) and prompts greater animal-based thermoregulation (NOAA, 2022).

Altogether, the strongest correlations were observed between primary animal-based indicators and T_{db} , with the highest correlation coefficient between ST_U and T_{db} ($r = 0.80$). This was in alignment with our hypothesis. Interestingly, despite climate or duration differences, these outcomes are relatively similar to correlations assessed in the group-housed subtropical calves (Dado-Senn et al., 2020) and hutch-housed continental calves (Kovács et al., 2018) with strong correlations between ST and T_{db} or THI ($r = 0.74$ to 0.85). Thus, ST could be used as an animal-based indicator of heat stress in dairy calves in various climates and housing styles when shading is available (Dado-Senn et al., 2020).

The animal-based indicators assessed herein reflect different aspects of thermoregulation. Rectal temperature, as a true reflection of core body temperature, is the gold standard to determine heat stress in homeotherms (Umphrey et al., 2001). However, quicker and less invasive methods like RR and ST indicate an attempt to lose heat via evaporation or convection (Idris et al., 2021). Dairy cattle thermoregulation necessitates integrative signaling between core body and peripheral temperature. Skin surface temperature rises under elevated ambient temperature as the calf increases peripheral blood circulation and sweating to promote heat loss (Romanovsky, 2007). But surface temperature is not equivalent to core body temperature, measuring lower than the core and increasingly reduced from core to periphery (Idris et al., 2021). Despite this limitation, monitoring thermal discomfort and potential heat stress via surface level infrared temperature is still effective and becoming increasingly common. Indeed, this technology has been used to detect or measure animal stress responses, infection, feed efficiency, and thermoregulation (Schaefer et al., 2004; Montanholi et al., 2008; Uddin et al., 2021). The affordability and time-effectiveness of ST measurement promotes easy implementation on farm.

In agreement with the stronger correlation coefficients for T_{db} relative to THI, the linear regressions in the present study indicate that models containing T_{db} better explain animal response variables compared with THI alone. Depending on the animal-based indicator, inclusion of RH or AS to models did not improve

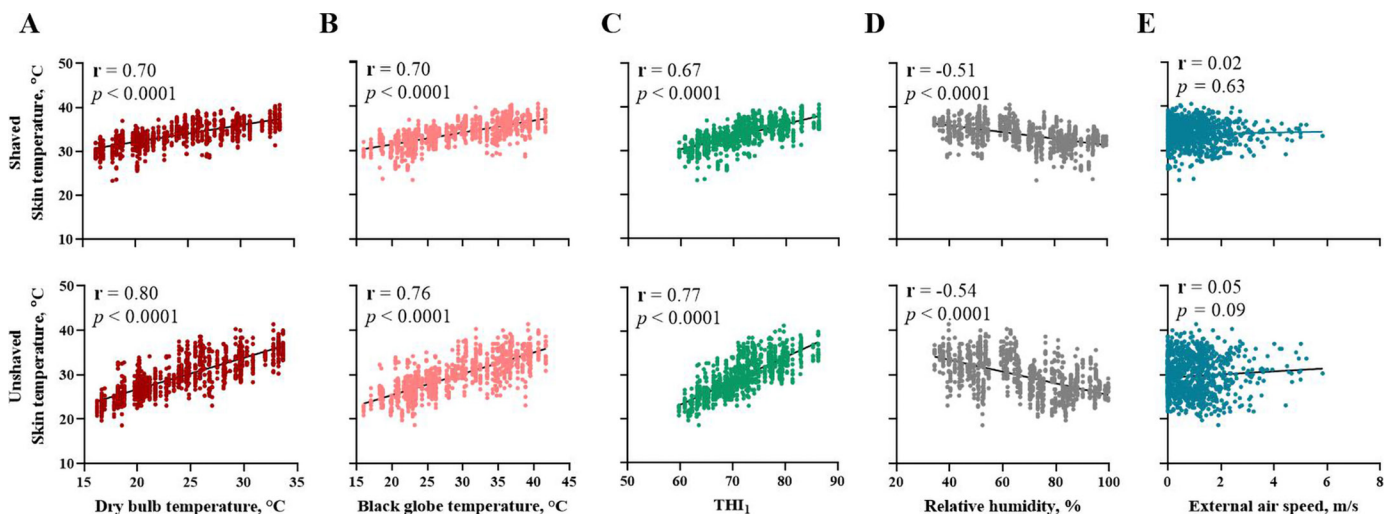


Figure 3. Correlations between environmental and animal-based indicator of heat stress [skin temperature (ST)]. Correlations between the animal-based indicator rump skin temperature from a shaved (ST_s) and unshaved (ST_U) area versus environmental indicators including dry bulb temperature (A, T_{db} , red), black globe temperature (B, T_{bg} , pink), temperature-humidity index (C; THI₁, THI equation 1, NRC, 1971, green), relative humidity (D, RH, gray), and external air speed (E, AS_{ext}, blue). Animal-based indicators and AS were recorded thrice weekly at 0700 and 1300 h with the former from outdoor hutch-housed dairy calves monitored over the summer in a continental climate. Other environmental measures were recorded every 15 min near hutches. Lines represent simple linear regression equations; P = significance of the correlation.

Table 4. Linear regressions to predict animal-based indicators¹

Model ^{2,3}	AIC	Pseudo R ²
Rectal temperature = T_{db}	474.1	0.69
Rectal temperature = RH	689.0	0.56
Rectal temperature = $T_{db} + RH$	484.1	0.68
Rectal temperature = THI_1	517.2	0.67
Rectal temperature = $THI_1 + AS_{ext}^{0.5}$	519.4	0.67
Rectal temperature = $T_{db} + RH + AS_{ext}^{0.5}$	487.5	0.69
Respiration rate = T_{db}	7,051.1	0.75
Respiration rate = RH	7,285.5	0.61
Respiration rate = $T_{db} + RH$	7,015.2	0.76
Respiration rate = THI_1	7,168.8	0.69
Respiration rate = $THI_1 + AS_{ext}^{0.5}$	7,090.7	0.69
Respiration rate = $T_{db} + RH + AS_{ext}^{0.5}$	6,938.3	0.76
Skin temperature, shaved = T_{db}	4,526.5	0.85
Skin temperature, shaved = RH	5,102.2	0.59
Skin temperature, shaved = $T_{db} + RH$	4,530.4	0.85
Skin temperature, shaved = THI_1	4,624.0	0.82
Skin temperature, shaved = $THI_1 + AS_{ext}^{0.5}$	4,573.7	0.82
Skin temperature, shaved = $T_{db} + RH + AS_{ext}^{0.5}$	4,481.0	0.85
Skin temperature, unshaved = T_{db}	3,893.3	0.74
Skin temperature, unshaved = RH	4,247.7	0.51
Skin temperature, unshaved = $T_{db} + RH$	3,899.6	0.73
Skin temperature, unshaved = THI_1	3,964.3	0.70
Skin temperature, unshaved = $THI_1 + AS_{ext}^{0.5}$	3,918.4	0.71
Skin temperature, unshaved = $T_{db} + RH + AS_{ext}^{0.5}$	3,853.7	0.75

¹Akaike information criterion (AIC), and pseudo R² for predicting rectal temperature (RT, °C), respiration rate (RR, breaths per minute), rump skin temperature from a shaved (ST_S, °C) and unshaved (ST_U, °C) area using various environmental variables in outdoor hutch-housed calves monitored over the summer in a continental climate. Pseudo R² was calculated based on the squared coefficient correlation obtained between predicted and observed values.

²A base model including age was used to adjust for measured variables but was not significant so removed.

³ T_{db} = dry bulb temperature, °C; RH = relative humidity, %; $AS_{ext}^{0.5}$ = external air speed, m/s; THI_1 = temperature-humidity index (NRC, 1971).

or only incrementally improved fit relative to T_{db} alone, while the model with RH or THI alone had poor fit. Together, this indicates that in a continental climate, T_{db} is the optimal environmental indicator of heat stress for hutch-housed calves instead of THI or RH. This aligns with results of acutely heat-stressed continental calves (Kovács et al., 2018) but contrasts results for subtropical, group-housed calves where THI was the optimal environmental indicator (Dado-Senn et al., 2020). Temperature-humidity index equations are formatted with various weights of T_{db} and RH or T_{db} and T_{wb} (a function of air temperature and RH) to account for the impact of environmental water vapor presence on animal heat loss mechanisms like evaporative cooling (Thom, 1959; NRC, 1971; Mader et al., 2006). Notably, all THI equations compared in the present study led to relatively similar correlation coefficients (except THI_5), similar to outcomes in subtropical lactating cows (Dikmen and Hansen, 2009). However, all THI relationships to calf animal-based indicators herein were still weaker when compared with T_{db} . Collectively, these results suggest that producers hutch-raising calves in a continental climate with reduced external humidity levels relative to a subtropical climate need only monitor

ambient temperature to detect thermal discomfort and heat stress, instead of using a comprehensive THI developed for lactating animals. These data also support the necessity to further develop THI models to better reflect continental environments and the responses of a growing dairy calf.

Temperature-humidity index or T_{db} thresholds, also described as breakpoints, are specific environmental values at which an abrupt change in animal response occurs. Temperature-humidity index breakpoints have been extensively assessed in adult dairy cattle for declines in milk yield, conception rate, or rumination or increases in thermoregulatory responses under heat stress (Pinto et al., 2020). Proposed THI thresholds range from 60 to 68 for milk yield reductions in more temperate continental climates (Brügemann et al., 2012; Herbut et al., 2015; Ouellet et al., 2019) or 68 to 72 in hotter subtropical climates (Ravagnolo et al., 2000; Zimbelman et al., 2009). Interestingly, THI breakpoints for thermoregulatory responses in continental lactating dairy cows are reported between 65 to 72, depending on the response measured (Pinto et al., 2020). Further THI thresholds for rising RR and RT are established between 72 and 78 for lactating and nonlactating sub-

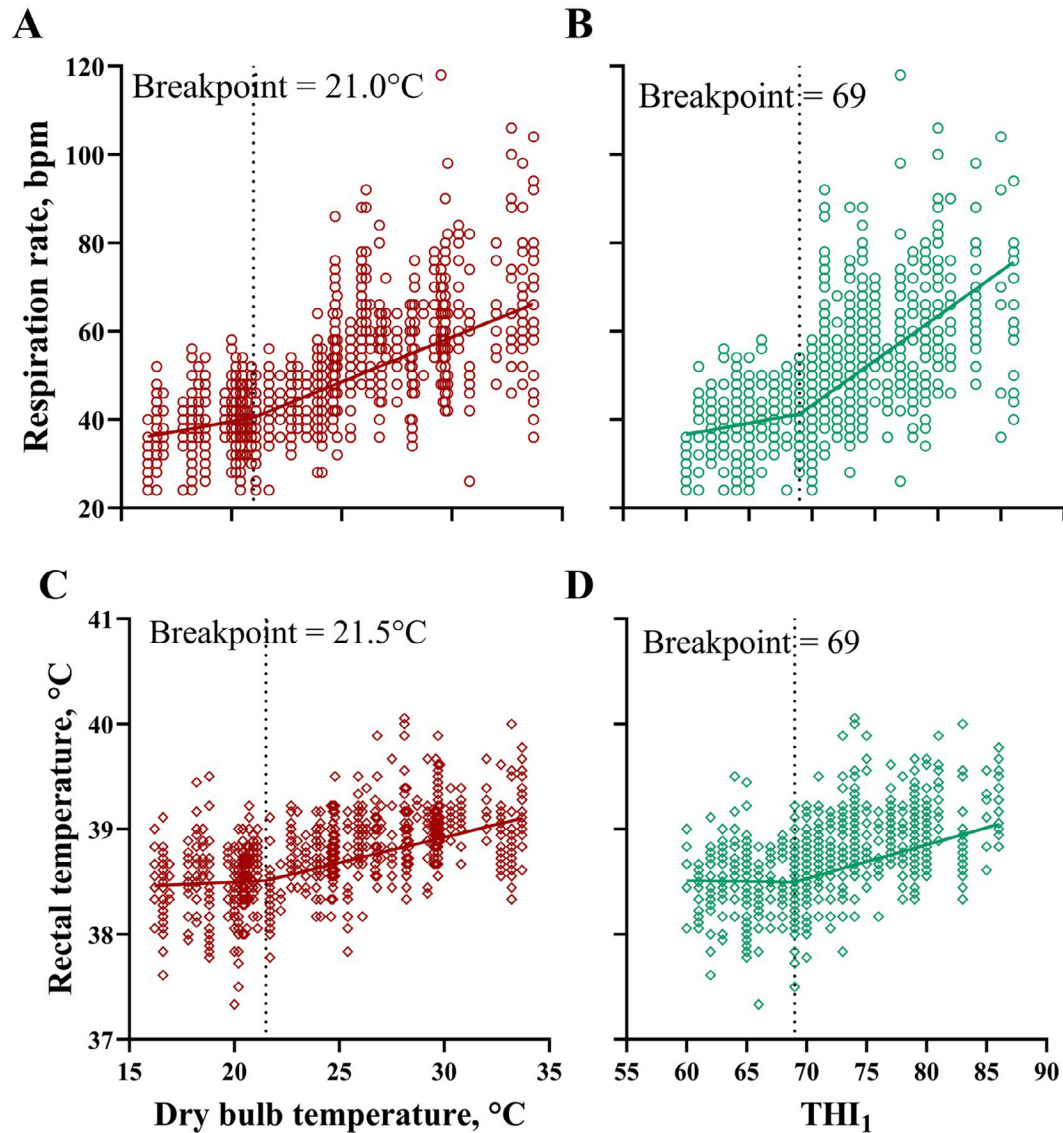


Figure 4. Breakpoints for animal-based indicators relative to environmental indicators. Segmented regressions of respiration rate (RR; A, B; circle symbols; bpm = breaths per minute) and rectal temperature (RT; C, D; diamond symbols) relative to dry bulb temperature (T_{db}) or temperature-humidity index (THI_1 , THI equation 1; NRC, 1971). Animal-based indicators were recorded thrice weekly at 0700 and 1300 h from outdoor hutch-housed dairy calves monitored over the summer in a continental climate. Environmental measures were recorded every 15 min near hutches. Lines represent segmented regression and dashes denote breakpoint at which the dependent variables changed significantly in calves.

tropical or tropical cows (da Costa et al., 2015; Ouellet et al., 2021).

More recently, interest has been generated in assessing breakpoints for nonproductive outcomes in dairy calves. Both T_{db} and THI were used to determine breakpoints in the present study to account for the strength of T_{db} association and the common inclusion of THI in heat stress assessment. Herein, calves hutch-raised across a continental climate summer had THI thresholds of 69 for both RR and RT, translated to 21.0°C and 21.5°C T_{db} , respectively. At these environ-

mental benchmarks, corresponding RR was 40 bpm and RT was 38.5°C. These outcomes are slightly higher but overall relatively similar to those of group-housed subtropical calves, where THI breakpoints were 65 and 67 for RR and RT for calves not provided heat abatement beyond shade (Dado-Senn et al., 2020). These breakpoints also align with the THI breakpoints established for thermoregulatory outcomes in continental lactating cows where the threshold was 70 for both RR and RT (Pinto et al., 2020).

However, the results herein greatly contrast those of a study of continental hutch-housed calves exposed to acute heat stress where THI breakpoints were 82 and 88 for RR and RT (Kovács et al., 2020). This large discrepancy, despite similarity in calf climate and housing, could be due to differences in the severity of heat stress exposure in the 2 studies. For instance, Kovács and co-authors assessed a severe bout of heat stress encompassing a higher, smaller range of THI, whereas the present study assessed thermal responses across the continental summer with a wider, more variable range of THI (61 to 77). It is likely that the THI thresholds of each study represent different stages of thermal response, as discussed by Silanikove (2000). We posit that the thresholds of the present study represent a shift from stage 1 to stage 2, where the calf increases thermoregulatory mechanisms to combat heat strain, thus experiencing thermal discomfort but maintaining homeothermy and productivity (Bianca, 1968; Silanikove, 2000; Van Os, 2019). Meanwhile, the thresholds of the severe, acute heat stress study represent calves shifting to stage 3, surpassing the upper critical temperature of the thermoneutral zone and negating homeothermy (Silanikove, 2000). Thus, the thresholds established herein are best used for situations of initial detection of thermal discomfort, allowing for intervention before more critical thermoregulatory or productive consequences.

The proper intervention following heat stress detection will vary depending on housing type and severity of heat stress. For continental, hutch-housed dairy calves, shading is an inexpensive and easily implemented option. Providing supplemental shade over the hutch can reduce air temperatures and inhibit solar radiation both inside and outside the hutch (Coleman et al., 1996; Spain and Spiers, 1996). Alternative adaptations to hutches, such as reflective hutch covers (Carter et al., 2014; Manriquez et al., 2018), hutch orientation (Bakony et al., 2021), or improving hutch ventilation (Moore et al., 2012; Reuscher et al., 2021) could also be explored. Research on shading or hutch modifications thus far has only detected improvements in hutch microclimate and animal thermoregulatory outcomes with no positive effects on body weight gain. Further investigation is also needed on proper calf bedding type in the summer. In the present study, calves were sand-bedded as a supposed mechanism of heat abatement (i.e., less heat generation relative to straw bedding). Sand bedding has been shown to negatively affect calf feed intake and scours incidence (Panivivat et al., 2004; Hill et al., 2011), but its influence on thermoregulatory outcomes is relatively unknown.

The impact of housing type on optimal continental calf indicators, breakpoints, and THI equation remains

unclear. It is likely that the improved ventilation capacity in certain group-housed calf facilities might require factoring in AS more so than hutch-housed calves, where internal AS is minimal, though it can be promoted through rear ventilation portholes (Moore et al., 2012; Dado-Senn et al., 2020; Reuscher et al., 2021). The hutch microclimate plays a complex role in the thermal status of calves, offering shade but increasing internal temperatures (Spain and Spiers, 1996). This is particularly relevant for hutch-housing situations where external access is limited. Thus, it is difficult to ascertain the role of the hutches in influencing the associations within and between animal-based and environmental indicators in the present study, as calves were hutch restricted before measurement of animal-based indicators, while environmental indicators were collected outside the hutches. Nevertheless, this experimental design reflects practical situations in which a producer might assess external environmental measures to detect heat stress for calves inside their hutches.

Further, typical hutch housing leads to both exposure to (i.e., hutch-external) and protection from (i.e., hutch-internal) solar radiation. In a continental summer environment, calves have been reported to spend between 75 to 90% of their time hutch-external between 14 and 42 d of age (Wormsbecher et al., 2017). Thus, there could be great impact of solar radiation on thermoregulatory outcomes. In the present study, calves had outdoor access but not at the time of animal-based indicator measurement. Thus, it was not surprising to find that the strength of correlations between T_{bg} (which accounts for solar radiation) and animal-based indicators were inconsistent relative to T_{db} and THI. The correlation between T_{bg} and RT was weaker relative to T_{db} and THI, but correlations between T_{bg} and RR/ST_S were roughly equivalent to T_{db} and stronger than THI. Notably, the THI equations explored herein do not account for solar radiation, so an environmental index that includes solar radiation (i.e., a heat load index; Lees et al., 2022) might be a better predictor of animal outcomes if animal-based indicators were to be measured hutch-external.

CONCLUSIONS

Hutch-raised dairy calves in a continental climate are susceptible to thermal discomfort and heat stress during summer, though outcomes differ from calf performance in subtropical chronic heat stress or continental acute heat stress. Herein, T_{db} was the optimal environmental thermal indicator. Environmental breakpoints reflecting abrupt changes in RR and RT were identified at a T_{db} around 21.0°C. When ambient environment reaches this threshold, calves should be closely monitored for

signs of thermal discomfort and heat abatement methods should be implemented. Proper identification and management of calf thermoregulation can mitigate the welfare concerns and production losses associated with hyperthermia.

ACKNOWLEDGMENTS




This research was funded by a Wisconsin Dairy Innovation Hub (DIH) short-term, high-impact grant awarded to J. Laporta at the University of Wisconsin-Madison (2021). We thank the Arlington Research Station and Blaine Research Dairy (Arlington, WI) staff, particularly Jessica Cederquist, Nathan Paiser, and Sierra Lurvey, for their assistance in calf management. The authors have not stated any conflicts of interest.

REFERENCES

- Bakony, M., G. Kiss, L. Kovács, and V. Jurkovich. 2021. The effect of hutch compass direction on primary heat stress responses in dairy calves in a continental region. *Anim. Welf.* 30:315–324. <https://doi.org/10.7120/09627286.30.3.009>.
- Beck, H. E., N. E. Zimmermann, T. R. McVicar, N. Vergopolan, A. Berg, and E. F. Wood. 2018. Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data* 5:180214. <https://doi.org/10.1038/sdata.2018.214>.
- Bianca, W. 1962. Relative importance of dry- and wet-bulb temperatures in causing heat stress in cattle. *Nature* 195:251–252. <https://doi.org/10.1038/195251a0>.
- Bianca, W. 1968. Thermoregulation. E. Hafez, ed. Lea & Febiger.
- Bohmanova, J., I. Misztal, and J. B. Cole. 2007. Temperature-humidity indices as indicators of milk production losses due to heat stress. *J. Dairy Sci.* 90:1947–1956. <https://doi.org/10.3168/jds.2006-513>.
- Brown-Brandl, T. M., R. A. Eigenberg, J. A. Nienaber, and G. L. Hahn. 2005. Dynamic response indicators of heat stress in shaded and non-shaded feedlot cattle, part 1: Analyses of indicators. *Biosyst. Eng.* 90:451–462. <https://doi.org/10.1016/j.biosystemseng.2004.12.006>.
- Brügemann, K., E. Gernand, U. König Von Borstel, and S. König. 2012. Defining and evaluating heat stress thresholds in different dairy cow production systems. *Arch. Tierzucht* 55:13–24. <https://doi.org/10.5194/aab-55-13-2012>.
- Carter, B. H., T. H. Friend, S. M. Garey, J. A. Sawyer, M. B. Alexander, and M. A. Tomazewski. 2014. Efficacy of reflective insulation in reducing heat stress on dairy calves housed in polyethylene calf hutches. *Int. J. Biometeorol.* 58:51–59. <https://doi.org/10.1007/s00484-012-0623-x>.
- Coleman, D. A., B. R. Moss, and T. A. McCaskey. 1996. Supplemental shade for dairy calves reared in commercial calf hutches in a southern climate. *J. Dairy Sci.* 79:2038–2043. [https://doi.org/10.3168/jds.S0022-0302\(96\)76577-3](https://doi.org/10.3168/jds.S0022-0302(96)76577-3).
- da Costa, A. N. L., J. V. Feitosa, P. A. Montezuma Jr., P. T. de Souza, and A. A. de Araújo. 2015. Rectal temperatures, respiratory rates, production, and reproduction performances of crossbred Girolando cows under heat stress in northeastern Brazil. *Int. J. Biometeorol.* 59:1647–1653. <https://doi.org/10.1007/s00484-015-0971-4>.
- Dado-Senn, B., K. N. Gingerich, K. C. Horvath, S. L. Field, M. G. Marrero, F. Maunsell, E. K. Miller-Cushon, and J. Laporta. 2022. Early-life heat stress exposure impacts dairy calf feeding and thermoregulatory behavior. *JDS Commun.* 3:38–43. <https://doi.org/10.3168/jdsc.2021-0110>.
- Dado-Senn, B., V. Ouellet, G. E. Dahl, and J. Laporta. 2020. Methods for assessing heat stress in pre-weaned dairy calves exposed to chronic heat stress or continuous cooling. *J. Dairy Sci.* 103:8587–8600. <https://doi.org/10.3168/jds.2020-18381>.
- Dikmen, S., and P. J. Hansen. 2009. Is the temperature-humidity index the best indicator of heat stress in lactating dairy cows in a subtropical environment? *J. Dairy Sci.* 92:109–116. <https://doi.org/10.3168/jds.2008-1370>.
- Galán, E., P. Llonch, A. Villagrà, H. Levit, S. Pinto, and A. del Prado. 2018. A systematic review of non-productivity related animal-based indicators of heat stress resilience in dairy cattle. *PLoS One* 13:e0206520. <https://doi.org/10.1371/journal.pone.0206520>.
- Herbut, P., W. Bieda, and S. Angrecka. 2015. Influence of hygrothermal conditions on milk production in a free stall barn during hot weather. *Anim. Sci. Pap. Rep.* 33:49–58.
- Hill, T. M., H. G. Bateman II, J. M. Aldrich, and R. L. Schlotterbeck. 2011. Comparisons of housing, bedding, and cooling options for dairy calves. *J. Dairy Sci.* 94:2138–2146. <https://doi.org/10.3168/jds.2010-3841>.
- Hoffmann, G., P. Herbut, S. Pinto, J. Heinicke, B. Kuhla, and T. Amon. 2020. Animal-related, non-invasive indicators for determining heat stress in dairy cows. *Biosyst. Eng.* 199:83–96. <https://doi.org/10.1016/j.biosystemseng.2019.10.017>.
- Idris, M., J. Uddin, M. Sullivan, D. M. McNeill, and C. J. C. Phillips. 2021. Non-invasive physiological indicators of heat stress in cattle. *Animals (Basel)* 11:71. <https://doi.org/10.3390/ani11010071>.
- IPCC. 2022. Climate Change 2022 (Impacts, Adaptation, and Vulnerability.) Intergovernmental Panel on Climate Change.
- Kovács, L., F. L. Kézér, P. Póti, N. Boros, and K. Nagy. 2020. Short communication: Upper critical temperature-humidity index for dairy calves based on physiological stress variables. *J. Dairy Sci.* 103:2707–2710. <https://doi.org/10.3168/jds.2019-17459>.
- Kovács, L., F. L. Kézér, F. Ruff, V. Jurkovich, and O. Szenci. 2018. Assessment of heat stress in 7-week old dairy calves with non-invasive physiological parameters in different thermal environments. *PLoS One* 13:e0208528.
- Laporta, J. 2022. Methods for detecting heat stress in hutch-housed dairy calves in a continental climate. Mendeley Data, V1. <https://doi.org/10.17632/k63rn3hm6y.1>.
- Lees, J. C., A. M. Lees, and J. B. Gaughan. 2022. The influence of shade availability on the effectiveness of the dairy heat load index (DHLI) to predict lactating cow behavior, physiology, and production traits. *Int. J. Biometeorol.* 66:289–299. <https://doi.org/10.1007/s00484-021-02186-x>.
- Léger, J., and J. Larochelle. 2006. On the importance of radiative heat exchange during nocturnal flight in birds. *J. Exp. Biol.* 209:103–114. <https://doi.org/10.1242/jeb.01964>.
- López, E., M. Mellado, A. M. Martínez, F. G. Véliz, J. E. García, A. de Santiago, and E. Carrillo. 2017. Stress-related hormonal alterations, growth and pelleted starter intake in pre-weaning Holstein calves in response to thermal stress. *Int. J. Biometeorol.* 62:493–500.
- Mader, T. L., M. S. Davis, and T. Brown-Brandl. 2006. Environmental factors influencing heat stress in feedlot cattle. *J. Anim. Sci.* 84:712–719. <https://doi.org/10.2527/2006.843712x>.
- Manriquez, D., H. Valenzuela, S. Paudyal, A. Velasquez, and P. J. Pinedo. 2018. Effect of aluminized reflective hutch covers on calf health and performance. *J. Dairy Sci.* 101:1464–1477. <https://doi.org/10.3168/jds.2017-13045>.
- Montanholi, Y. R., N. E. Odongo, K. C. Swanson, F. S. Schenkel, B. W. McBride, and S. P. Miller. 2008. Application of infrared thermography as an indicator of heat and methane production and its use in the study of skin temperature in response to physiological events in dairy cattle (*Bos taurus*). *J. Therm. Biol.* 33:468–475. <https://doi.org/10.1016/j.jtherbio.2008.09.001>.
- Moore, D. A., J. L. Duprau, and J. R. Wenz. 2012. Short communication: Effects of dairy calf hutch elevation on heat reduction, carbon dioxide concentration, air circulation, and respiratory rates. *J. Dairy Sci.* 95:4050–4054. <https://doi.org/10.3168/jds.2012-5397>.
- National Animal Health Monitoring System (NAHMS). 2016. Dairy Cattle Management Practices in the United States, 2014: Report 1. USDA, Animal and Plant Health Inspection Service, Veterinary

- Services, Centers for Epidemiology and Animal Health, and National Animal Health Monitoring System.
- National Oceanic and Atmospheric Administration (NOAA). 2022. Why does wind blow? Accessed Apr. 21, 2022. <https://scijinks.gov/wind/>.
- NRC. 1971. A Guide to Environmental Research on Animals. Natl. Acad. Sci.
- Nguyen, J. L., J. Schwartz, and D. W. Dockery. 2014. The relationship between indoor and outdoor temperature, apparent temperature, relative humidity, and absolute humidity. *Indoor Air* 24:103–112. <https://doi.org/10.1111/ina.12052>.
- Ouellet, V., I. M. Toledo, B. Dado-Senn, G. E. Dahl, and J. Laporta. 2021. Critical temperature-humidity index thresholds for dry cows in a subtropical climate. *Front. Anim. Sci.* 2:706636. <https://doi.org/10.3389/fanim.2021.706636>.
- Ouellet, V., V. E. Cabrera, L. Fadul-Pacheco, and E. Charbonneau. 2019. The relationship between the number of consecutive days with heat stress and milk production of Holstein dairy cows raised in a humid continental climate. *J. Dairy Sci.* 102:8537–8545. <https://doi.org/10.3168/jds.2018-16060>.
- Panivivat, R., E. B. Kegley, J. A. Pennington, D. W. Kellogg, and S. L. Krumpelman. 2004. Growth performance and health of dairy calves bedded with different types of materials. *J. Dairy Sci.* 87:3736–3745. [https://doi.org/10.3168/jds.S0022-0302\(04\)73512-2](https://doi.org/10.3168/jds.S0022-0302(04)73512-2).
- Pinto, S., G. Hoffmann, C. Ammon, and T. Amon. 2020. Critical THI thresholds based on the physiological parameters of lactating dairy cows. *J. Therm. Biol.* 88:102523. <https://doi.org/10.1016/j.jtherbio.2020.102523>.
- Ravagnolo, O., I. Misztal, and G. Hoogenboom. 2000. Genetic component of heat stress in dairy cattle, development of heat index function. *J. Dairy Sci.* 83:2120–2125. [https://doi.org/10.3168/jds.S0022-0302\(00\)75094-6](https://doi.org/10.3168/jds.S0022-0302(00)75094-6).
- Reuscher, K. J., C. S. Yu, R. Salter, T. Bresolin, and J. M. C. Van Os. 2021. Effects of hutch ventilation on preference and heat stress in pair-housed dairy calves. *J. Dairy Sci.* 104:201.
- Roland, L., M. Drillich, D. Klein-Jöbstl, and M. Iwersen. 2016. Invited review: Influence of climatic conditions on the development, performance, and health of calves. *J. Dairy Sci.* 99:2438–2452. <https://doi.org/10.3168/jds.2015-9901>.
- Romanovsky, A. A. 2007. Thermoregulation: Some concepts have changed. Functional architecture of the thermoregulatory system. *Am. J. Physiol. Regul. Integr. Comp. Physiol.* 292:R37–R46. <https://doi.org/10.1152/ajpregu.00668.2006>.
- Schaefer, A. L., N. Cook, S. V. Tessaro, D. Deragt, G. Desroches, P. L. Dubeski, A. K. W. Tong, and D. L. Godson. 2004. Early detection and prediction of infection using infrared thermography. *Can. J. Anim. Sci.* 84:73–80. <https://doi.org/10.4141/A02-104>.
- Silanikove, N. 2000. Effects of heat stress on the welfare of extensively managed domestic ruminants. *Livest. Prod. Sci.* 67:1–18. [https://doi.org/10.1016/S0301-6226\(00\)00162-7](https://doi.org/10.1016/S0301-6226(00)00162-7).
- Spain, J. N., and D. E. Spiers. 1996. Effects of supplemental shade on thermoregulatory response of calves to heat challenge in a hutch environment. *J. Dairy Sci.* 79:639–646. [https://doi.org/10.3168/jds.S0022-0302\(96\)76409-3](https://doi.org/10.3168/jds.S0022-0302(96)76409-3).
- Stull, C., and J. Reynolds. 2008. Calf welfare. *Vet. Clin. North Am. Food Anim. Pract.* 24:191–203. <https://doi.org/10.1016/j.cvfa.2007.12.001>.
- Thom, E. C. 1959. The discomfort index. *Weatherwise* 12:57–61. <https://doi.org/10.1080/00431672.1959.9926960>.
- Uddin, J., C. J. C. Phillips, M. Auboeuf, and D. M. McNeill. 2021. Relationships between body temperatures and behaviours in lactating dairy cows. *Appl. Anim. Behav. Sci.* 241:105359. <https://doi.org/10.1016/j.applanim.2021.105359>.
- Umphrey, J. E., B. R. Moss, C. J. Wilcox, and H. H. Van Horn. 2001. Interrelationships in lactating Holsteins of rectal and skin temperatures, milk yield and composition, dry matter intake, body weight, and feed efficiency in summer in Alabama. *J. Dairy Sci.* 84:2680–2685. [https://doi.org/10.3168/jds.S0022-0302\(01\)74722-4](https://doi.org/10.3168/jds.S0022-0302(01)74722-4).
- Van Laer, E., C. P. H. Moons, B. Sonck, and F. A. M. Tuytens. 2014. Importance of outdoor shelter for cattle in temperate climates. *Livest. Sci.* 159:87–101. <https://doi.org/10.1016/j.livsci.2013.11.003>.
- Van Os, J. M. C. 2019. Considerations for cooling dairy cows with water. *Vet. Clin. North Am. Food Anim. Pract.* 35:157–173. <https://doi.org/10.1016/j.cvfa.2018.10.009>.
- Wormsbecher, L., R. Bergeron, D. Haley, A. M. de Passillé, J. Rushen, and E. Vasseur. 2017. A method of outdoor housing dairy calves in pairs using individual calf hutches. *J. Dairy Sci.* 100:7493–7506. <https://doi.org/10.3168/jds.2017-12559>.
- Yousef, M. K. 1985. *Stress Physiology in Livestock. Vol. I, Basic Principles.* 1st ed. M. K. Yousef, ed. CRC Press.
- Zimbelman, R. B., R. P. Rhoads, M. L. Rhoads, G. C. Duff, L. H. Baumgard, and R. J. Collier. 2009. A re-evaluation of the impact of temperature humidity index (THI) and black globe humidity index (BGHI) on milk production in high producing dairy cows. Pages 158–169 in *Southwest Nutrition & Management Conference*.

ORCIDS

- B. Dado-Senn  <https://orcid.org/0000-0002-6104-7334>
 V. Ouellet  <https://orcid.org/0000-0003-0260-3246>
 J. Van Os  <https://orcid.org/0000-0002-7107-2867>
 J. Laporta  <https://orcid.org/0000-0002-3186-5360>