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Chapter 5: Thermal Indices and Their Applications for Livestock Environments

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Introduction

Heat exchanges with the environment are crucial processes for maintaining homeothermy by humans and other animals. These exchanges involve heat production, conservation, and dissipation, and are dependent on both biological and physical factors. The complexity of these exchanges has led to many attempts to represent the environmental aspects by surrogate thermal indices as a basis for assessing the biological effect and consequent impact of the thermal environment. Resultant index values represent effects produced by the heat exchange process. For humans, comfort assessment is primary; for animals, assessing performance, health, and well-being have been foremost. Emphasis in this chapter is on thermal indices used in animal studies and their applications, with a view toward strategic and tactical decisions for rational environmental management. Illustrative examples are included, as are considerations for future efforts.

Historically, most efforts to develop thermal indices have been for human applications, and involve both psychological and physiological aspects. Jendritzky et al. (2002) states that more than 100 such indices have been developed over the past 150 years, usually based on two thermal parameters to represent the complex heat exchanges between the human body and the thermal environment. Ideally, "...each index value will always result in a unique thermophysiological effect, regardless of the combination of the input meteorological input values" (Jendritzky et al., 2002).¹ This utopian goal is unattainable in reality for thermal indices representing livestock environments because of the complex interactions of the environment and animal factors,

¹ Table 29.4 of the *Handbook of Applied Meteorology* (edited by Houghton, 1985) lists representative biometeorological indices developed for human applications, ranging from the simple to the complex.

which result in a variety of responses depending on species and individual animal characteristics.

Contrary to the focus of human-oriented thermal indices on comfort, the primary emphasis for domestic animals has been on indices to support rational environmental management decisions related to performance, health, and well-being (Hahn and McQuigg, 1970a; Hahn, 1976, 1995). These animal-related indices recognize the ability of the animal to cope with environmental stressors (within limits) by adjusting physiologically, behaviorally, and immunologically to minimize adverse effects (Hahn, 1999), or even compensate for reduced growth performance during moderate environmental challenges (Hahn, 1982). Only when the magnitude (intensity and duration) of potential stressors exceeds thresholds, coupled with limited opportunity for recovery, are animals unable to cope and therefore are affected adversely (see Figure 1 and related discussions in Chapter 1). Most of the effort to develop thermal indices for livestock has focused on moderate to high temperature conditions because of the higher risk of such environments for homeothermic animals. The effects of cold conditions on animals are relatively limited when nutritional needs are adequate, and vulnerable animals are usually housed.

For farm animals, thermal indices have nevertheless served as useful surrogates for the complex interactions between the physical and biological components (Hahn et al., 2003). As such, indices have been used to provide guides for environmental management and assessment of risk for losses through linkages with responses related to physiology (Eigenberg et al., 2005) or animal performance (Hahn and McQuigg, 1970a; Hahn, 1976; Baccari, 2001). The linkage is based on observations of a selected performance criterion (e.g., growth, milk, or egg production) made concurrently with measures of the thermal environment. These serve as inputs for the selected thermal index and thus an empirical relationship (termed a *biologic response function* by Hahn and McQuigg, 1970b) can be developed. This emphasizes the biological consequences associated with the index values. Additionally, if the same thermal index is selected for the response functions of multiple performance criteria and species, there is opportunity for broader application of the index climatology (e.g., through development of probability information).

The focus of this chapter is on indices representing the influence of thermal environments on farm animal responses, and applications of those indices as the basis for environmental management of livestock. Examples are included to enhance understanding of the background and application of specific approaches used to assess the impact of thermal conditions, and considerations are suggested that may be useful in the further development of thermal indices for animal studies and management applications.

The Development of Thermal Indices for Animals

As discussed in Chapter 1 in the Psychrometrics section, dry-bulb temperature provides a measure of the sensible heat content of air, and represents a major portion of the driving force for heat exchange between the environment and an animal. However, other measures of the thermal environment also impact the total heat exchange, includ-

ing latent heat content of the air, as represented by some measure of the insensible heat content (e.g., dew-point temperature or humidity), thermal radiation (shortwave and longwave), and airflow.

Yamamoto (1983) provides a good discussion of the influence of humidity, air movement, and thermal radiation on heat exchanges related to effective temperatures. He concluded that “Heat exchanges between animals and their thermal environment are not [readily] explainable in terms of physical principles because the relationships are considerably modified [by] animal factors.” In part, this reflects physiological differences among species in sensible and latent heat dissipation as they respond to the heat exchange parameters, as summarized by Esmay (1969). Behavioral aspects (e.g., huddling or burrowing in bedding during cold; wetting skin surfaces in hot conditions) also can markedly alter heat exchanges.

Because of the limitations of air temperature alone as a representative measure of the thermal environment, there have been many efforts to combine the effects of two or more thermal measures representing the influence of sensible and latent heat exchanges between the organism and its environment. It is important to recognize that all such efforts produce *index values*, rather than a true temperature (even when expressed on a temperature scale). As such, an index value represents the *effect* produced by the heat exchange process, which can alter the biological response that might be associated with changes in temperature alone. In the case of humans, the useful effect is the sensation of comfort; for animals, the useful effect is the impact on performance, health, and well-being.

It also should be recognized that indices are mathematical models, which never truly represent the complexity of the physical/biological interactions; for example, index relationships are typically linear, while real-world relationships are not. Nevertheless, thermal indices have value as secondary measures, serving as surrogates for the complex interactions between the physical and biological components (Hahn et al., 2003). Thresholds, above or below which animals are adversely affected by the thermal environment, are crucial elements for consideration in the development and use of thermal indices. Further, static responses of organisms to thermal environments are generally assumed; in reality, the responses are temporally dynamic and involve interactions within the biological system (c.f. Hahn, 1989, 1999; Giuseppe and Giovanni, 2002).

Indices Related to Animal Responses

Indices Based on Wet- and Dry-Bulb Temperatures

A wet-/dry-bulb temperature index (WD Index) for growing-finishing swine (typically 30-90 kg bodyweight) in acute heat conditions was experimentally determined by Roller and Goldman (1969), based on ambient dry-bulb (T_{db}) temperatures from 34° to 43°C and wet-bulb (T_{wb}) temperatures from 23° to 31°C. Their research correlated four physiological parameters (skin temperature, rectal temperature, respiration rate, and heart rate) to these temperature conditions, as:

$$\text{Swine WD Index} = 0.75T_{db} + 0.25T_{wb} \quad (1)$$

This WD Index was later tested by Nelson et al. (1972) for its application to determine swine performance under naturally varying summer conditions in Kentucky as well as air conditioned, evaporative-cooled, and mist-cooled environments. Nelson et al.

(1972) substituted the WD Index temperature for the dry-bulb temperature of the swine production curves of Hazen and Mangold (1960) and found the WD Index adequately predicted the performance decline of 30-40 kg to market pigs in warm environments as well as the swine performance in the other three investigated environments.

For smaller swine (20-30 kg), Ingram (1965) found a slightly higher sensitivity to T_{wb} , with the coefficients being 0.65 and 0.35 for T_{db} and T_{wb} , respectively. A series of physiological studies with poultry have determined coefficients for T_{db}/T_{wb} : 0.60/0.40 for laying hens (Zulovich and DeShazer, 1990); 0.74/0.26 for 16-wk-old hen turkeys (Xin et al., 1992); and 0.53/0.47 for 6-wk-old tom turkeys to 0.42/0.58 for 20-wk-old tom turkeys (Brown-Brandl et al., 1997). The poultry researchers used the term Temperature Humidity Index (THI) instead of WD Index for each of the species investigated. For example, the laying hen WD Index is identified as THI_{layers} . The latter research indicated that tom turkeys are more sensitive to a humid environment as they become more mature.

Zulovich and DeShazer (1990) estimated egg production declines, egg breakage, and egg weight declines from equations by Timmons and Gates (1988) for warm humid environments using the laying hen WD Index (a.k.a. THI_{layers}) substituted for dry-bulb temperature. From this information they calculated the energy requirements and thus feed consumption based on equations by Greninger et al. (1982). With this result they predicted the economic impact of warm-humid environments on laying hen production. As an example, they determined that the maximum net income occurred between 23° and 24°C at 50% RH, based on 1990 feed cost and egg prices.

Additionally, Gates et al. (1991) used the THI_{layers} for evaluating misting rates for poultry, and also established regional variations of the THI_{layers} for poultry housing (Gates et al., 1995). More details of these studies by Gates and colleagues are given in Chapter 7, "Modeling of Animal Bioenergetics for Environmental Management Applications."

Swine and poultry are basically non-sweating species, so that air moisture content has less influence than for species having a better ability to dissipate heat through skin vaporization. For beef cattle, a species with more capabilities to dissipate latent heat through the skin, Bianca (1962) developed a relationship which indicates a greater sensitivity to air moisture content, with coefficients of 0.35 and 0.65 for T_{db} and T_{wb} , respectively. Thus, the use of evaporative cooling could be more effective for swine and poultry as compared to cattle.

The Temperature-Humidity Index

The Temperature-Humidity Index² or THI, shown in chart form in Figure 1 as adapted from the Discomfort Index for humans developed by Thom (1959), has been extensively applied for moderate to hot conditions using a response function approach, even with recognized limitations related to airspeed and radiation heat loads. Temperature and humidity influence much of the heat exchange impacts of warm and hot thermal environments, and hence often adequately represent the overall impact on livestock (Hahn, 1995; St-Pierre et al., 2003; Brown-Brandl et al., 2005). The THI has

² THI can be calculated from the following equations, where dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and dew-point temperature (T_{dp}) are °C and relative humidity (RH) is %: $THI = 0.72 (T_{db} + T_{wb}) + 40.6$; $THI = T_{db} + (0.36 T_{dp}) + 41.2$; $THI = 0.8T_{db} + RH(T_{db} - 14.4) + 46.4$.

		Relative Humidity, %																			
Temperature, °C		5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
	21	64	64	64	65	65	65	66	66	66	67	67	67	68	68	68	69	69	69	70	70
	22	65	65	65	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71	72	72
	23	66	66	67	67	67	68	68	69	69	70	70	71	71	71	72	72	73	73	74	74
	24	67	67	68	68	69	69	70	70	71	71	72	72	73	73	74	74	75	75	76	76
	26	68	68	69	69	70	70	71	71	72	73	73	74	74	75	75	76	76	77	77	78
	27	69	69	70	70	71	72	72	73	73	74	75	75	76	76	77	78	78	79	79	80
	28	69	70	71	71	72	73	73	74	75	75	76	77	77	78	79	79	80	81	81	82
	29	70	71	72	73	73	74	75	75	76	77	78	78	79	80	80	81	82	83	83	84
	30	71	72	73	74	74	75	76	77	78	78	79	80	81	81	82	83	84	84	85	86
	31	72	73	74	75	76	76	77	78	79	80	81	81	82	83	84	85	86	86	87	88
	32	73	74	75	76	77	78	79	79	80	81	82	83	84	85	86	86	87	88	89	90
	33	74	75	76	77	78	79	80	81	82	83	84	85	85	86	87	88	89	90	91	92
	34	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94
	36	76	77	78	79	80	81	82	83	85	86	87	88	89	90	91	92	93	94	95	96
	37	77	78	79	80	82	83	84	85	86	87	88	89	90	91	93	94	95	96	97	98
	38	78	79	80	82	83	84	85	86	87	88	90	91	92	93	94	95	97	98	99	100
	39	79	80	81	83	84	85	86	87	89	90	91	92	94	95	96	97	98	100	101	102
	40	80	81	82	84	85	86	88	89	90	91	93	94	95	96	98	99	100	101	103	104
	41	81	82	84	85	86	88	89	90	91	93	94	95	97	98	99	101	102	103	105	106
	42	82	83	85	86	87	89	90	92	93	94	96	97	98	100	101	103	104	105	107	108
	43	83	84	86	87	89	90	91	93	94	96	97	99	100	101	103	104	106	107	109	110

Categories of Livestock Weather Safety Index associated with THI values:

Normal: ≤ 74 Alert: 75-78 Danger: 79-83 Emergency: ≥84

Figure 1. Temperature-Humidity Index (THI) chart (based on Thom, 1959). Associated Livestock Weather Safety Index (LWSI; LCI, 1970) categories are also shown.

for several years served as a *de facto* standard for classifying thermal environments in many animal production and transport situations, and a basis for strategic and tactical management practices during seasons other than winter.

The earliest example of the application of the THI as the basis for livestock response functions was for milk production decline (MDEC, kg/cow-day) of dairy cows, which was linked to the THI by means of the equation (Berry et al., 1964):

$$\text{MDEC} = 1.075 - 1.736 M + 0.02474 M \times \text{THI} \quad (2)$$

where M = normal level of milk production in thermoneutral conditions, kg/cow-day.

This response function was developed through observations of responses of lactating dairy cows during exposure for several days to a selected regime of air temperatures and humidities while housed in environmental chambers (low airflow and nil radiation load, i.e., mean radiant temperature equals air temperature). The lower threshold THI for observed adverse effects on milk production is about 72-74, depending on the normal level of production (lower for high-producing cows and higher for low production levels). Mayer et al. (1999) reported that milk production was affected at a lower THI value of 72 where no shade was provided, and that the threshold can be adjusted upward to 78 where shade and sprinklers are used. Attempts have also been made to link the THI with changes in feed intake of dairy cows (Hahn and Osburn, 1969; Roseler et al., 1997) and beef cattle (DeDios and Hahn, 1993; Hahn and Mader, 1997).

Reproduction of dairy cows also has been linked to the THI based on field observations in Mexico and Hawaii (Ingraham et al., 1974), and in Australia (Jonsson et al.,

1997; Morton et al., 2007). The conception rate of dairy cows was studied by Morton et al. (2007) over a three-year period in Australia. They reported a strong correlation between increasing THI values and decreasing conception rate (Figure 2). Amundson et al. (2006) used 10 years of calving data to evaluate the THI effects on reproduction in grazing beef cows. These authors reported that for the 0-60 day breeding period the optimum THI was 68. Reductions in pregnancy rates of beef cows decreased when $\text{THI} > 72.9$.

Even with the obvious limitations on the THI-based MDEC response function for dairy cows (e.g., disregard of airflow and thermal radiation components of the environment), it has been successfully used in a variety of research studies and management applications. Initially, it was used to estimate milk production declines during summer months for shaded dairy cows in various U.S. locations, based on climatological analyses of the THI (Figure 3; Hahn and Osburn, 1969; Hahn and McQuigg, 1970b). These estimated production declines compared favorably (within 4%-15%) with actual declines measured during summertime trials in four divergent U.S. locations (Hahn, 1969). Other climatic analyses of the THI have since been completed for other U.S. locales (e.g., Huhnke et al., 2001) and for several other dairy production areas of the world, where summer conditions cause reductions in production and reproduction. Examples of the latter include Argentina (Valtorta et al., 1998; de la Casa and Ravelo, 2003), Australia (Davison et al., 1996), Brazil (da Silva, 2000), and South Africa (du Preez et al., 1990). The response function has also been used to estimate the benefits of environmental modification practices for shaded lactating cows, such as evaporative cooling (Figure 3; Hahn and Osburn, 1970).

Monitoring animal performance in controlled-environment chambers over longer periods of time (weeks to months) permits development of response functions, such as for growth, milk production or other performance measures as functions of thermal

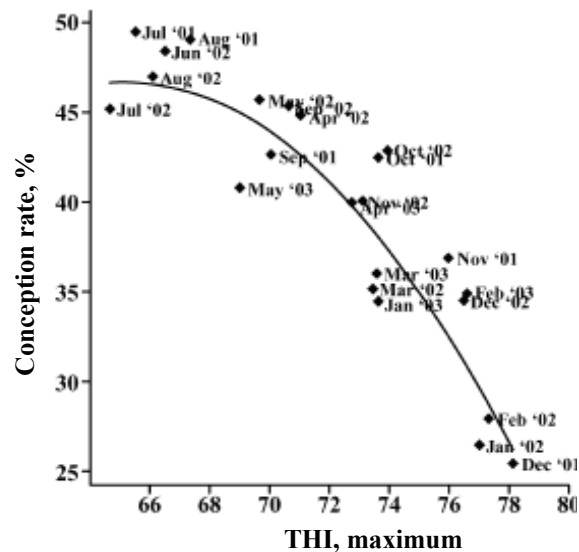


Figure 2. The relationship between THI values and conception rate in dairy cows (Morton et al., 2007).

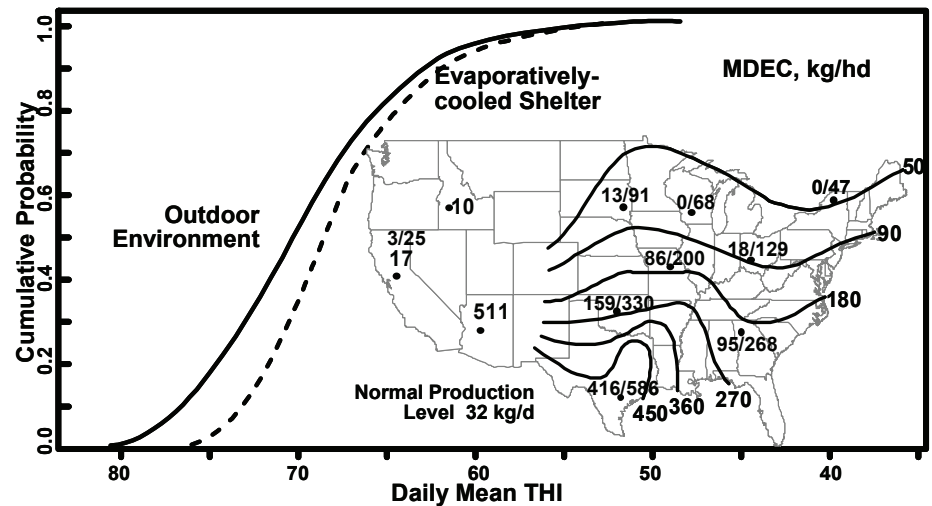


Figure 3. Probability distribution functions for daily mean THI in the naturally varying outdoor environment and in evaporative-cooled shelters (adapted from Hahn and Osburn, 1969) at Columbia, Missouri, during the June 1-Sept 30 summer season. The inset U.S. map shows associated expected milk production declines (MDEC) for dairy cows with a 32 kg/d normal production level (Hahn and McQuigg, 1970b), along with 10th and 90th percentile values for selected locations (i.e., in central Missouri, 1 yr in 10 milk decline would be expected to be as low as 86 kg for the 122 day period, and 1 yr in 10 it would be as high as 200 kg, compared to the 180 kg average for that location).

parameters (e.g., t_{db} or the Temperature-Humidity Index THI; Hahn et al., 2003). In the development of such response functions, however, compensatory capabilities of the animals may affect the threshold for performance losses, as they have considerable ability to rebound after stressors are removed (Hahn, 1982). Compensatory capabilities seem to exist for a relatively broad range of factors for which performance penalties are slight to moderate. Obviously, there are linkages between the dynamic, short-term responses which influence feed intake and the longer-term performance responses which depend on feed intake.

The THI has also been used as the basis for the Livestock Weather Safety Index (LWSI) to describe categories of heat stress associated with hot-weather conditions for livestock exposed to extreme conditions (LCI, 1970), as denoted in Figure 1. The LWSI serves as a tactical guide for mitigating the effects of challenging environmental conditions on animals in intensive production systems, as well as during transport. For many years, the U.S. Agricultural Weather Advisory Service (AWAS) provided daily early-morning advisories when the LWSI was forecast to be in the Alert and higher categories, so that livestock personnel could plan to limit handling of animals and consider use of tactical measures to protect them. Since abolishment of the AWAS because of budgetary cutbacks in the U.S., some private weather services provide such advisories to subscribers for a fee. In New Zealand, the Meteorological Service currently provides heat-stress forecasts for dairy cows at www.metservice.co.nz/data/hsigraph.

In connection with extreme summertime conditions, the THI has recently been used to evaluate spatial and temporal aspects of the development of heat waves (Hahn and

Mader, 1997; Hubbard et al., 1999). For cattle in feedlots, a THI-based classification scheme has also been developed to assess the potential impact of heat waves (Hahn et al., 1999) using a retrospective analysis of heat wave events over a 42-yr period that resulted in extensive feedlot cattle deaths in a Nebraska location, and based on the criteria that a heat wave was at least 3 days duration with THI >70 for all hours. The classifications incorporated persistence and nighttime cooling using a THI-hours approach³ to assess the magnitude (intensity × duration) of the heat wave events which put the animals at risk (Table 1). THI-hrs are developed using the same approach as used for heating degree-days and cooling degree-days, with an appropriate base. In this case, the LWSI thresholds for Danger and Emergency categories (THI >79 and THI >84, respectively), were used as the base, with hourly values computed from weather records.

The THI-hrs approach used for classifying heat waves has also been used in a recent assessment of likelihood of occurrence of heat waves (personal communication, Eric Bowles, 2007). Climatic conditions were evaluated using more than 50 years of hourly weather records for 39 stations in the central United States. The number of each type of heat-stressing event (slight, mild, moderate, strong, severe, and extreme) was tabulated for every year based on the THI thresholds of 75, 79, and 84. Results were used to determine the probability of occurrence of a major heat wave event in the central United States, as shown in Figure 4.

Concerns with potential climate change impacts of animal agriculture have also led to the use of the THI for assessing such impacts on production and related measures.

Table 1. Descriptive characteristics for heat wave categories for *Bos taurus* feedlot cattle exposed to single heat wave events (Hahn et al., 1999).^[a]

Category	Duration	THI-hrs > 79	THI-hrs >84	Nighttime Recovery (hrs < 72 THI)
1. Slight	limited: 3-4 d	10-25/d	none	good: 5-10h/night
2. Mild	limited: 3-4 d	18-40/d	<5/d	some: 3-8h/night
3. Moderate	more persistent: 4-6 d	25-50/d	<6/d	reduced: 1-6h/night
4. Strong	increased persistence: 5-7 d	33-65/d	<6/d	limited: 0-4h/night
5. Severe	very persistent: 6-8 d	40-80/d	3-15/d on 3 or more successive days	very limited: 0-2h/night
6. Extreme	very persistent: 6-10 d	50-100/d	15-30/d on 3 or more successive days	nil:<1h/night over 3 or more d

^[a] Environmental factors other than temperature and humidity (e.g., solar radiation, wind speed) and biological factors (e.g., heat tolerance/sensitivity, diet, acclimation to heat) can modify the potential impact of given environments on feedlot cattle. Severe to extreme category conditions can be lethal for vulnerable cattle when combined with high solar radiation levels and low wind speeds, especially when maximum THI is 86 or higher; such conditions were prevalent in the 1995 heat wave which caused more than 4000 feedlot cattle deaths in the central United States (Hahn and Mader, 1997).

³ The daily THI-hrs were calculated from $\text{Daily THI-hrs} = \sum_{\text{hr}=1}^{24} (\text{THI} - \text{base}) \cdot$

For example, the effects on milk production have been evaluated for either potential global cooling resulting from supersonic transport planes (Johnson et al., 1975) or current concerns about possible global warming associated with fossil fuel use and other human activities (Hahn et al., 1992; Klinedinst et al., 1993; Valtorta et al., 1995). Numerous other examples of such usage are in the Proceedings of the International Livestock Environment Symposia series (published by ASABE) which began in 1974.

Relationships for long-term strategic decisions (e.g., evaluating the need for and selection of economical environmental modification practices) must recognize the ability of animals to acclimatize during long-term exposure to challenging thermal environments. Response relationships useful for short-term tactical decisions (day-to-day operations, such as handling practices and use of heating/cooling equipment), must recognize the dynamics of the animal response to short-term environmental challenges, such as reported for cattle by Hahn (1999). The outcome of current applications of this dual approach, even with the limitations of current information, has been improved production, health, and well-being of animals in adverse climates, especially during weather extremes.

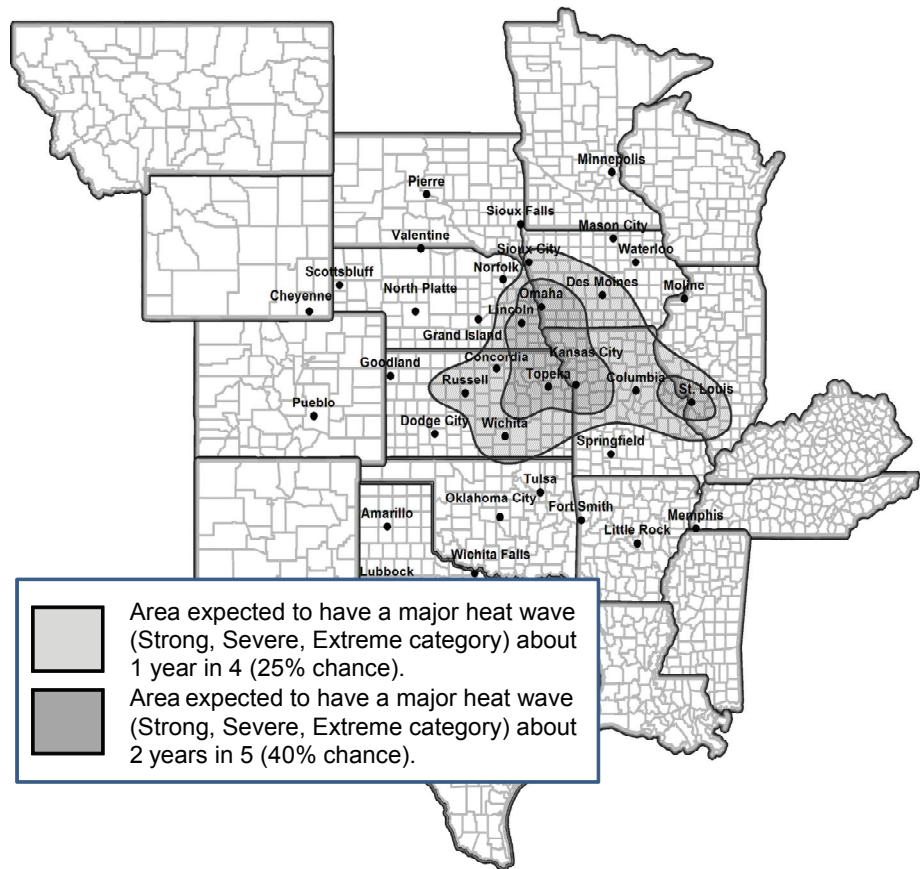


Figure 4. The extent of expected major heat wave occurrence across the central United States (based on communication with Eric Bowles, 2007).

Modifications to the THI

Various modifications to the THI have been proposed to overcome shortcomings related to lack of inclusion of airflow and radiation heat loads. An example is the Black-Globe Temperature-Humidity Index (BGTHI; Buffington et al., 1981), which uses black-globe temperature (Bond and Kelly, 1955) instead of dry-bulb temperature in the THI equation. Applications of the BGTHI to dairy cows suggested that values of 70 or below had little impact, while values of 75 or higher markedly reduce feed intake (Buffington et al., 1981). More recently, Buffington and others agree that a threshold of 75 for marked reduction in feed intake is likely too high given the current milk production levels, genetics, and use of bovine somatotropin (Gooch and Inglis, 2001).

Other corrections to the THI have been proposed, particularly for use with feedlot cattle, based on recent research by Mader and Davis (2002) and Eigenberg et al. (2005) using measures of wind speed (WS) and solar radiation (SR). On the basis of the impact on panting score (Mader and Davis, 2002), THI was adjusted as follows:

$$THI_{adj} = 4.51 + THI - 1.992 WS + 0.0068 SR \quad (3)$$

where WS = wind speed, m/s

SR = solar radiation, W/m².

For a range of conditions from 15°C to 40°C and 35% to 90% RH, hourly THI adjustments as evaluated by Mader et al. (2006) were +0.7 for an increase in SR of 100 W/m², and –2.4 for a WS increase of 1 m/s, based on panting scores of observed animals; adjustments to daily THI means were 1.14 and –3.08 for SR and WS, respectively.

Respiration rate (RR) has also been shown to be a good indicator of stress level (Hahn et al., 1997; Gaughan et al., 2000; Eigenberg et al., 2005). Respiration rates of unshaded animals penned individually during daylight hours were observed by Eigenberg et al. (2005) during summer months and compared with recorded temperature (T_{db} , °C), dew point (T_{dp}) or relative humidity (RH, %), wind speed (m/s) and solar radiation (W/m²). A functional relationship was developed for RR (no shade, $T_{db} > 25^\circ\text{C}$):

$$RR = 2.8T_{db} + 2.4T_{dp} - 1.5WS + 0.038SR - 52.8 \quad (4)$$

The relationship was used to develop equivalent RR thresholds for THI categories, assuming a solar radiation load of 800 W/m², a wind speed of 0 m/s, dry-bulb temperature range of 25 to 40°C, and relative humidity between 30 and 50% (Table 2).

Comparatively, the equivalent hourly THI adjustments from observations of RR as determined by Eigenberg et al. (2005) were +3.9 and –1.7, respectively, for the same

Table 2. Respiration rates associated with Temperature-Humidity Index thresholds (Eigenberg et al., 2005).

Threshold	THI	Respiration Rate, breaths/min
Normal	74 or less	< 90
Alert	74 to <79	90 to 110
Danger	79 to <84	110 to 130
Emergency	84 and above	>130

increases in SR and WS as used by Mader et al. (2006). While the proposed adjustment factor differences are substantial, there were differences in the types and number of animals used in the two studies. Nevertheless, the approach appears to merit further research to establish acceptable THI corrections, perhaps for a variety of animal parameters.

Other Approaches to the Development of Thermal Indices for Animals

Gaughan et al. (2008) developed a Heat Load Index (HLI) as a guide to the management of *Bos taurus*, *Bos indicus*, and *Bos taurus* × *Bos indicus* feedlot cattle during hot weather. The HLI was developed following observation of behavioral responses (respiration rate, panting score, shade seeking, location in pen [e.g., at water trough]) and changes in dry matter intake of feedlot steers (n = 17,750) representing 7 genotypes over 8 summers. Thirteen feedlot locations were used (10 in Australia and 3 in USA). In addition to the cattle data, climatic data were collected from automated weather stations located at each site. The HLI is based on humidity (RH, %), wind speed (WS, m/s), and black-globe temperature (BGT, °C). Where BGT cannot be measured directly a predicted BGT can be computed (EA Systems, 2002) from air temperature (T_{db} , °C) and solar radiation (SR, W/m²):

$$\text{Predicted BGT} = 1.33 \times T_{db} - 2.65 \times T_{db}^{0.5} + 3.21 \times \log_{10}(\text{SR} + 1) + 3.5 \quad (5)$$

The HLI consists of two parts based on a black-globe temperature threshold of 25°C:

$$\text{HLI}_{\text{BGT} > 25} = 8.62 + 0.38 \text{ RH} + 1.55 \text{ BGT} - 0.5 \text{ WS} + e^{(2.4 - \text{WS})} \quad (6)$$

where e is the base of the natural logarithm, and:

$$\text{HLI}_{\text{BGT} < 25} = 10.66 + 0.28 \text{ RH} + 1.3 \text{ BGT} - \text{WS} \quad (7)$$

A base threshold was developed (HLI = 86) for unshaded Angus steers. Adjustments to the base threshold are subsequently made on the basis of genotype (e.g., for *Bos indicus* the HLI threshold is 96), coat color (e.g., for white coat the HLI threshold is 89), health status (e.g., the threshold is 81 if the animal is sick), access to shade (e.g., the threshold is 93 where steers have access to 3.0 m² of shade per animal), days on feed manure management (i.e., the number of days between pen cleaning), and drinking water temperature. The threshold adjustments were developed on the basis of changes in respiratory dynamics (primarily changes in panting score) and increases in tympanic temperature; other threshold adjustments are provided in Table 3. The thresholds are used to calculate the accumulated heat load (AHL) to which the cattle are exposed. The AHL is based on the THI-hours concept of Hahn and Mader (1997). When an animal is exposed to a HLI above its threshold, the core body temperature increases, and this is the basis for calculating AHL. The longer the duration of exposure to a HLI above the threshold the greater the stress (i.e., the greater the accumulated heat load). The AHL also accounts for any potential recovery during nighttime cooling. Therefore the AHL gives an indication of the total heat load on the animal, and is a better indicator of thermal stress than a spot measure of HLI.

Table 3. Animal (genotype, coat color, health status, acclimatization) and management (access to shade, days on feed, manure management and drinking water temperature) adjustments (+ and -) to the heat load index (HLI) threshold (86) of the reference steer (healthy unshaded Angus, 100 days on feed), from Gaughan et al. (2008).

Item	Number of cattle ^[a] used to determine the specific threshold	Relative effect on upper HLI threshold of the reference steer (HLI = 86)
Genotype:		
<i>Bos taurus</i> (British)	9,075	0 ^[b]
<i>Bos taurus</i> (European)	429	+ 3 (i.e., 86 + 3)
Waygu	894	+ 4
<i>Bos indicus</i> (25%)	451	+ 4
<i>Bos indicus</i> (50%)	1,345	+ 7
<i>Bos indicus</i> (75%)	1,039	+ 8
<i>Bos indicus</i> (100%)	666	+ 10
Coat Color:		
Black	2,859	0
Red	1,158	+ 1
White	293	+ 3
Health Status:		
Healthy	15,623	0
Sick/recovering	1,987	- 5
Acclimatization:		
Acclimated	6,200	0
Not acclimated	2,920	- 5
Shade: ^[c]		
No Shade	3,467	0
Shade (>1.5 to 2 m ² /animal)	1,336	+ 3
Shade (>2.0 to 3 m ² /animal)	6,473	+ 5
Shade (>3.0 m ² /animal)	4,761	+ 7
Days on Feed: ^[d]		
0 to 80 d	2,672	+ 2
80 to 130 d	8,385	0
>130 d	1,239	- 3
Manure Management: ^[e]		
Max. depth of manure pack = 50 mm	3,224	0
Max. depth of manure pack = 100 mm	704	- 4
Max. depth of manure pack = 200 mm	220	- 8
Drinking Water Temperature: ^[f]		
15° to 20°C	224	+ 1
21° to 30°C	2,035	0
31° to 35°C	399	- 1
>35°C	201	- 2
^[a] Not all cattle have been assessed within each threshold trait. For example, coat color was only assessed in <i>Bos taurus</i> cattle, manure management at 5 feedlots and drinking water temperature was assessed on three feedlots. ^[b] The values for the reference steer are presented as 0, i.e. no change from the threshold of 86. ^[c] For shade that provides 70% block out (includes shade cloth and also steel structures with gaps in the roof). Unshaded <i>Bos indicus</i> cattle > 25 % not included. ^[d] Not all cattle were assessed for this trait. Waygu cattle excluded from 130 + d. ^[e] Mean depth over 54 days ^[f] Only unshaded Angus cattle were assessed for this trait.		

The HLI and the AHL have now been implemented as a heat load warning guide on the Internet (www.katestone.com.au/mla), as both a current and 5-day forecast for Australian producers. In addition the HLI and AHL form a portion of the annual risk assessment undertaken by commercial feedlots in Australia as part of the quality assurance program.

Using the approach that animals themselves provide an integrated response to their thermal environment, the linear-regression-based estimator developed by Eigenberg et al. (2005) for RR of unshaded feedlot cattle at temperature levels above 25°C (described earlier in Equation 4) serves as the basis for alerting feedlot managers to possible thermal stress in their animals. This relationship has been further used to implement an environmental monitoring device for guidance in managing livestock production facilities (Eigenberg et al., 2003) and is currently used in conjunction with U.S. National Weather Service forecasts for online heat wave alerts (ars.usda.gov/main/site_main.htm?modecode=54-38-00-00; click on “Cattle Heat Stress” link). See Chapter 6 for further details.

Baeta et al. (1987) developed an Equivalent Temperature Index (ETI) for dairy cows in above-thermoneutral conditions, which combined the effects of air temperature and humidity with airspeed to evaluate the impacts on heat dissipation and milk production (Figure 5). So far, the ETI has not been widely accepted, perhaps because of being based on limited (3-day) treatment observation periods which do not adequately reflect longer-term effects. Nevertheless, it may provide representative results for short-term heat challenges that often occur in the summer season.

A somewhat similar approach was used to derive an Apparent Equivalent Temperature (AET) from air temperature and vapor pressure to develop “thermal comfort zones” for transport of broiler chickens (Mitchell et al., 2001). Experimental studies to

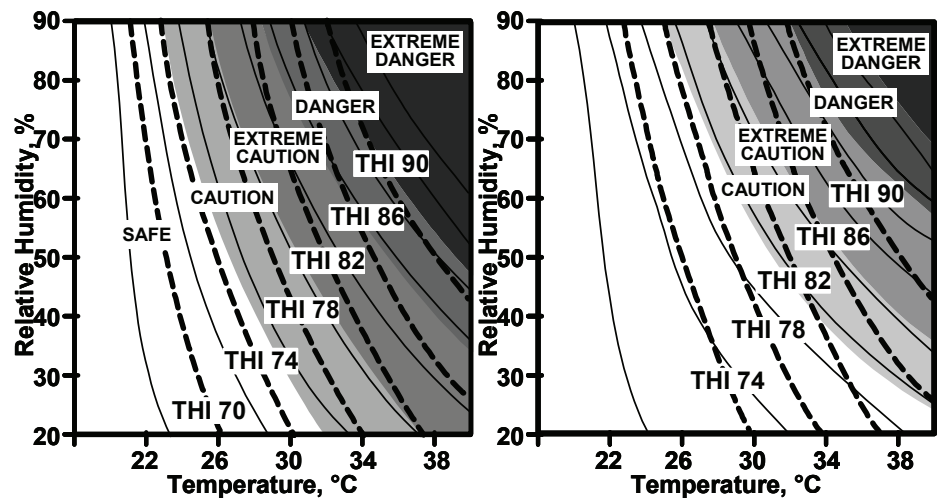


Figure 5. Equivalent Temperature Index (ETI) as a function of ambient temperature and humidity at wind speeds of 0.5 m/s (left) and 6 m/s (right), with associated categories of potential impact on dairy cows (Baeta et al., 1987). Values of THI are superimposed for comparison.

link the AET with increased body temperature during exposure to hot conditions indicated potential for improved transport practices. For cold-weather conditions, Ames and Insley (1975) developed wind-chill equations for cattle and sheep, which recognize the considerable effect of hair coat on heat exchange with the surroundings.

Considerations for Further Development of Thermal Indices for Animals

The success of the THI, particularly for cattle applications, has been useful for development of rational decision-making information for livestock managers. That does not mean it is the best thermal index that can be developed for all livestock applications, because of its limitations related to thermal radiation, airflow, and cold conditions. Additionally, there are species-specific limitations (e.g., non-sweating swine and poultry, which respond quite differently to warm environments than cattle). There are even limited cases where air temperature alone has been shown to be an adequate representation of the impact of hot thermal environments; for example, an evaluation of predictors of thermal variable effects on rectal temperature of lactating cows in a subtropical environment (Dikman and Hansen, 2009). It should also be noted that in intensive animal housing with environmental modification, temperature alone is also the usual control parameter. However, by combining temperature and humidity effects, the THI does capture much of the impact of warm to hot thermal environments on animals.

Nevertheless, efforts should continue for improving on the basic THI and THI-hrs concepts by incorporating the effects of thermal radiation and airflow, especially for animals in unsheltered moderate to hot environments and for animals in cold conditions. The substitution of black-globe temperature for air temperature to obtain the BGHI (Buffington et al., 1981) appears to be useful in some applications, and adding modifiers to the THI to recognize thermal radiation and wind effects on animals in unsheltered environments (as suggested for feedlot cattle: Mader and Davis, 2002; Eigenberg et al., 2005) may have promise. The HLI (Gaughan et al., 2008) uses black-globe temperature, relative humidity, and wind speed as the climatic inputs and is currently being used by the Australian feedlot industry. The HLI is currently being modified for use with dairy cows. Other approaches, such as the Apparent Equivalent Temperature proposed by Mitchell et al. (2001) for use in poultry transport, also may be appropriate. Enthalpy has been suggested as an alternative thermal index by Beckett (1965) for swine and by Moura et al. (1997) for swine and poultry.

The success of THI-based environmental management for livestock, as discussed in this chapter, lies not in the THI being the best possible thermal index, but in the development of biologic response functions that link important animal responses to an appropriate index which in turn serves as a surrogate to reflect complex heat exchanges between the thermal environment and the animal. Relationships for long-term strategic decisions (e.g., evaluating the need for and selection of economical environmental-modification practices) must recognize the ability of animals to acclimatize during long-term exposure to challenging thermal environments. Response relationships useful for short-term tactical decisions (day-to-day operations, such as handling practices

and use of heating/cooling equipment), must recognize the dynamics of the animal response to short-term environmental challenges. The outcome of current applications of this dual approach, even with the limitations of current information, has been improved environmental management, which benefits production, health, and well-being of animals in adverse climates, especially during weather extremes.

Any modified or replacement index must be pragmatic in the face of limited resources available for development and application. Regardless of the level of sophistication, thermal indices need to be developed in a way that improves on the foundation of applications that have served livestock managers well in their decision-making process. That means any improved index will ideally be useful as a basis for continued development of biologic response functions, and representative of the consequences resulting from primary factors influencing energy exchanges between the animal and its surroundings. For strategic decision-making, a proliferation of indices, each with limited application, is not recommended. Instead, the goal should be an index that is broadly applicable or readily adjustable across life stages and species, in order to maximize the utility of probability information about the index. For tactical decisions, modifiers for indices that focus more on the animal's immediate physiological responses to heat exchanges with the thermal environment may be appropriate. An alternative for tactical decisions is observation of the animals themselves as an integrator of the impact of the thermal environment (Young et al., 1997; Eigenberg et al., 2005), keeping in mind that tactical action is required at early signs of heat stress to prevent or minimize performance losses.

References

- Ames, D. A., and L. W. Insley. 1975. Wind-chill effect for cattle and sheep. *J. Anim. Sci.* 40(1): 161-165.
- Amundson, J. L., T. L. Mader, R. J. Rasby, and Q. S. Hu. 2006. Environmental effects on pregnancy rate in beef cattle. *J. Anim. Sci.* 84: 3415-3420.
- Baccari, F., Jr. 2001. Manejo ambiental da vacaleiteira em climas quentes. Editora da Universidade Estadual de Londrina. Londrina PR-Brazil. 142 pp.
- Baeta, F. C., N. F. Meador, M. D. Shanklin, and H. D. Johnson. 1987. Equivalent temperature index at temperatures above the thermoneutral for lactating dairy cows. ASAE Paper No. 874015. St. Joseph, Mich.:ASAE.
- Beckett, F. E. 1965. Effective temperature for evaluating or designing hog environments. *Trans. ASAE* 8(2): 163-166.
- Berry, I. L., M. D. Shanklin, and H. D. Johnson. 1964. Dairy shelter design based on milk production decline as affected by temperature and humidity. *Trans. ASAE* 7(3): 329-331.
- Bianca, W. 1962. Relative importance of dry- and wet-bulb temperatures in causing heat stress in cattle. *Nature* 195: 251-252.
- Bond, T. E., and C. F. Kelly. 1955. The globe thermometer in agricultural research. *Agric. Eng.* 36: 251-255, 260.
- Bowles, E. (Kansas State Univ., Dept of Geography). 2007. Personal communication with G.L. Hahn.
- Brown-Brandl, T. M., M. M. Beck, D. D. Schulte, A. M. Parkhurst, and J. A. DeShazer. 1997. Temperature-Humidity Index for growing tom turkeys. *Trans. ASAE* 49(1): 203-209.
- Brown-Brandl, T. M., R. A. Eigenberg, and J. A. Nienaber. 2006. Heat stress risk factors of feedlot heifers. *Livestock Science* 105: 57-68.
- Buffington, D. E., A. Collazon-Arocho, G. H. Canton, and D. Pitt. 1981. Black globe-humidity index (BGHI) as comfort equation for dairy cows. *Trans. ASAE* 24(3): 711-714.
- da Silva, R.G. 2000. *Introducao a bioclimatologia animal*. Sao Paulo, Brazil: Noble. 286 pp.
- Davison, T., M. McGowan, D. Mayer, B. Young, N. Jonsson, A. Hall, A. Matschoss, P. Goodwin, J. Gaughan, and M. Lake. 1996. *Managing Hot Cows in Australia*. Brisbane, Australia: QDPI.

- DeDios, O. O., and G. L. Hahn. 1993. Thermoregulation of growing bovines during fall transitional environments. In *Livestock Environment IV, Proc. 4th Intl. Livestock Environment Symposium*, 289-297. E. Collins and C. Boon, eds. St. Joseph, Mich.: ASAE.
- de la Casa, A., and A. C. Ravelo. 2003. Assessing temperature and humidity conditions for dairy cattle in Cordoba, Argentina. *Intl. J. Biometeorology* 48: 6-9.
- 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.
- du Preez, J. H., W. H. Giesecke, and P. J. Hattingh. 1990. Heat stress in dairy cattle and other livestock under southern African conditions. I. Temperature- Humidity Index mean values during the four main seasons. *Onderstepoort J. Vet. Res.* 57: 77-87.
- EA Systems. 2002. Final Report. FLOT.317: Measuring the microclimate of Eastern Australian feedlots, 40-44. Sydney, Australia: Meat and Livestock.
- Eigenberg, R. A., T. M. Brown-Brandl, J. A. Nienaber, and G. L. Hahn. 2005. Dynamic response indicators of heat stress in shaded and non-shaded feedlot cattle. Part 2: Predictive relationships. *Biosystems Eng.* 91(1): 111-118.
- Eigenberg, R. A., J. A. Nienaber, and T. M. Brown-Brandl. 2003. Development of a livestock safety monitor for cattle. ASAE Paper No. 032338. St. Joseph, Mich.: ASAE.
- Esmay, M. L. 1969. *Principles of Animal Environment*. Westport Conn.: AVI Publ. 325 pp.
- Gates, R. S., M. B. Timmons, and R. W. Bottcher. 1991. Numerical optimization of evaporative misting systems. *Trans. ASAE* 34(1): 275-280.
- Gates, R. S., S. H. Zhang, D. G. Colliver, and D. G. Overhults. 1995. Regional variation in temperature humidity index for poultry housing. *Trans. ASAE* 38(1): 197-205.
- Gaughan, J. B., T. L. Mader, S. M. Holt, and A. Lisle. 2008. A new heat load index for feedlot cattle. *J. Anim. Sci.* 86: 226-234.
- Gaughan, J. B., S. M. Holt, G. L. Hahn, T. L. Mader, and R. Eigenberg. 2000. Respiration rate—Is it a good measure of heat stress in cattle? *Asian-Australas. J. Anim. Sci.* 13: 329-332.
- Gooch, C. A., and S. F. Inglis. 2001. Environmental conditions in plastic film covered calf facilities. In *Livestock Environment VI, Proc. 6th Intl. Livestock Environment Symposium*, 703-715. R. R. Stowell, R. Bucklin, and R. W. Bottcher, eds. St. Joseph, Mich.: ASAE.
- Giuseppe, P., and C. Giovanni. 2002. Biological rhythm in livestock. *J. Veterinary Sci.* 3(3): 145-157.
- Greninger, T. L., J. A. DeShazer, and E. W. Gleaves. 1982. Simulation of poultry energetics for developing environmental recommendations. In *Livestock Environment II, Proc. 2nd Intl. Livestock Environment Symposium*, 234-240. St. Joseph, Mich.: ASAE.
- Hahn, G. L. 1969. Predicted vs. measured production differences using summer air conditioning for lactating dairy cows. *J. Dairy Sci.* 52(6): 800-802.
- Hahn, G. L. 1976. Rational environmental planning for efficient livestock production. *Biomet.* 6 (Part II): 106-114.
- Hahn, G. L. 1981. Housing and management to reduce climatic impacts on livestock. *J. Anim. Sci.* 52(1): 175-186.
- Hahn, G. L. 1982. Compensatory performance in livestock: influences on environmental criteria. In *Livestock Environment II, Proc. 2nd Intl. Livestock Environment Symposium*, 284-294. St. Joseph, Mich.: ASAE.
- Hahn, G. L. 1989. Body temperature rhythms in farm animals. *Proc. 11th Intl. Congress of Biometeorology*, 325-337. The Hague: SPB Publishing.
- Hahn, G. L. 1995. Environmental management for improved livestock performance, health and well-being. *Japanese J. Livestock Mgmt.* 30(3): 113-127.
- Hahn, G. L. 1999. Dynamic responses of cattle to thermal heat loads. *J. Anim. Sci.* 77 (Suppl. 2): 10-20.
- Hahn, G. L., and D. D. Osburn. 1969. Feasibility of summer environmental control for dairy cattle based on expected production losses. *Trans. ASAE* 12(4): 448-451.
- Hahn, G. L., and D. D. Osburn. 1970. Feasibility of evaporative cooling for dairy cattle based on expected production losses. *Trans. ASAE* 13(3): 289-291, 294.
- Hahn, G. L., and J. D. McQuigg. 1970a. Expected production losses for lactating Holstein dairy cows as a basis for rational planning of shelters. *Intl. J. Farm Bldgs. Res.* 4: 2-8.
- Hahn, G. L., and J. D. McQuigg. 1970b. Evaluation of climatological records for rational planning of livestock shelters. *Aric. Meteorol.* 7(2): 131-141.

- Hahn, G. L., and T. L. Mader. 1997. Heat waves in relation to thermoregulation, feeding behavior and mortality of feedlot cattle. In *Livestock Environment V, Proc. 5th Intl. Livestock Environment Symposium*, 563-571. R. W. Bottcher and S. J. Hoff, eds. St. Joseph, Mich.: ASAE.
- Hahn, G. L., P. L. Klinedinst, and D. A. Wilhite. 1992. Climate change impacts on livestock production and management. ASAE Paper 927037. St Joseph, Mich.:ASAE.
- Hahn, G. L., A. M. Parkhurst, and J. B. Gaughan. 1997. Cattle respiration rate as a function of ambient temperature. ASAE Paper No. MC97-121, St Joseph, Mich.: ASAE.
- Hahn, G. L., T. L. Mader, J. B. Gaughan, Q. Hu, and J. A. Nienaber. 1999. Heat waves and their impacts on feedlot cattle. *Proc. 15th Intl. Cong. of Biomet. and Intl. Cong. Urban Climatology*. Sydney, Australia: ISB.
- Hahn, G. L., T. L. Mader, and R. A. Eigenberg. 2003. Perspectives on development of thermal indices for animal studies and management. In *Proc. Symp. Interactions between Climate and Animal Production*, 31-44. Published as EAAP Technical Series No. 7.
- Hazen, T. E., and D. W. Mangold. 1960. Functional and basic requirements of swine housing. *Agric. Eng.* 41(9): 585-590.
- Houghton, D. D., ed. 1985. *Handbook of Applied Meteorology*. New York: John Wiley and Sons.
- Hubbard, K. G., D. E. Stooksbury, G. L. Hahn, and T. L. Mader. 1999. A climatological perspective on feedlot cattle performance and mortality related to the temperature-humidity index. *J. Production Agric.* 12: 650-653.
- Huhnke, R. L., L. C. McCowan, G. M. Meraz, S. L. Harp, and M. E. Payton. 2001. Determining the frequency and duration of elevated Temperature-Humidity Index. ASAE Paper No. 014111. St Joseph, Mich.:ASAE.
- Ingram, D. L. 1965. The effect of humidity on temperature regulation and cutaneous water loss in the young pig. *Res. Vet. Sci.* 6(1): 9-17.
- Ingraham, R. H., D. D. Gillette, and W. D. Wagner. 1974. Relationship of temperature and humidity to conception rate of Holstein cows in subtropical climate. *J. Dairy Sci.* 57: 476-481.
- Jendritzky, G., A. Maarouf, D. Fiala, and H. Staiger. 2002. An update on the development of a Universal Thermal Climate Index. In *Proc. 15th AMS Conf. on Biomet. and Aerobiology/16th Intl. Cong. Biomet.*, 129-133. Boston, Mass.: AMS.
- Johnson, H. D., G. L. Hahn, and D.E. Buffington. 1975. Animal husbandry implications. Sect. 4.3 in CIAP Monograph 5, Impacts of Climate Change on the Biosphere (Final Report). Climatic Impact Assessment Program (Stratospheric Pollution by Aircraft), Dept. of Transportation. 423 pp.
- Jonsson, N. N., M. R. McGowan, K. McGuigan, T. M. Davison, A. M. Hussain, M. Kafi, and A. Matschoss. 1997. Relationships among calving season, heat load, energy balance and postpartum ovulation of dairy cows in a subtropical environment. *Anim. Reprod. Sci.* 47: 315-326.
- Klinedinst, P. L., D. A. Wilhite, G. L. Hahn, and K.G. Hubbard. 1993. The potential effects of climate change on summer season dairy cattle milk production and reproduction. *Climate Change* 23: 21-36.
- LCI. 1970. Patterns of transit losses. Omaha, Neb.: Livestock Conservation, Inc.
- Mader, T. L., and M. S. Davis. 2002. Wind speed and solar radiation correction for the Temperature-Humidity Index. *Proc. 16th Cong. Intl. Soc. Biomet./15th Am. Met. Soc. Conf. Biomet. and Aerobiol.*, 154-157. Boston, Mass.: AMS.
- 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.
- Mayer, D. G., T. M. Davison, M. R. McGowan, B. A. Young, A. L. Matschoss, A. B. Hall, P. J. Goodwin, N. N. Jonsson, and J. B. Gaughan. 1999. Extent and economic effect of heat loads on dairy cattle production in Australia. *Aust. Vet. J.* 77:804-808.
- Mitchell, M. A., P. J. Kettlewell, R. R. Hunter, and A. J. Carlisle. 2001. Physiological stress response modeling—Applications to the broiler transport thermal environment. In *Livestock Environment VI, Proc. 6th Intl. Livestock Environment Symposium*, 550-555. R. R. Stowell, R. Bucklin, and R. W. Bottcher, eds. St. Joseph, Mich.: ASAE.
- Morton, J. M., W. P. Tranter, D. G. Mayer, and N. N. Jonsson. 2007. Effects of environmental heat on conception rates in lactating dairy cows: Critical periods of exposure. *J. Dairy Sci.* 90:2271-2278.
- Moura, D. J., I. A. Naas, K. B. Sevegnani, and M. E. Corria. 1997. The use of enthalpy as a thermal comfort index. In *Livestock Environment V, Proc. 5th Intl. Livestock Environment Symposium*, 577-583. R. W. Bottcher and S. J. Hoff, eds. St. Joseph, Mich.: ASAE.
- Nelson, D. P., C. H. Read, B. J. Barfield, J. N. Walker, V. Hayes, and G. Cromwell. 1972. The performance of swine under warm environments. *Trans. ASAE* 15(1):133-136.

- Osburn, D. D., and G. L. Hahn. 1968. Economics of environmental control for livestock. *Can. J. Agr. Economics* 16(3): 116-120.
- Roller, W. L., and R. F. Goldman. 1969. Response of swine to acute heat exposure. *Trans. ASAE* 12(2): 164-169, 174.
- Roseler, D. K., D. G. Fox, A. N. Pell, and L. E. Chase. 1997. Evaluation of alternative equations for prediction of intake in Holstein dairy cows. *J. Dairy Sci.* 80 :864-877.
- St-Pierre, N. R., B. Cobanov, and G. Schnitkey. 2003. Economic losses from heat stress by US livestock industries. *J. Dairy Sci.* 86(Suppl. E): E52-E77.
- Thom, E. C. 1959. The Discomfort Index. *Weatherwise* 12: 57-60.
- Timmons, M. B., and R. S. Gates. 1988a. Predictive model of laying hen performance to air temperature and evaporative cooling. *Trans. ASAE* 31(5): 1503-1509.
- Valtorta, S. E., P. E. Leva, L. V. Fornasero, and J. Bardin. 1995. Horas de estres para el ganado en Argentina: Situación actual e impacto esperado del cambio climático global. (Stress hours for cattle in Argentina: present situation and expected effect of global warming.) *Proc. 1st Brazilian Biometeorological Congress (Jaboticabal, SP, Brazil, 275-285.*
- Valtorta, S., P. Leva, H. Castro, M. Gallardo, M. Maciel, A. Guglielmone, and O. Anziani. 1998. Producción de leche en verano, p. 18. Santa Fe, Argentina: Universidad Nacional del Litoral. 105 pp.
- Xin, H., J. A. DeShazer, and M. M. Beck. 1992. Responses of pre-fasted growing turkeys to acute heat exposure. *Trans. ASAE* 35(1): 315-318.
- Yamamoto, S. 1983. The assessment of thermal environment for farm animals. *Proc. 5th World Cong. Animal Prod.* 1: 197-204.
- Young, B. A., A. B. Hall, P. J. Goodwin, and J. B. Gaughan. 1997. Identifying excessive heat load. In *Livestock Environment V, Proc. 5th Intl. Livestock Environment Symposium*, 572-576. R. W. Bottcher and S. J. Hoff, eds. St. Joseph, Mich.: ASAE.
- Zulovich, J. M., and J. A. DeShazer. 1990. Estimating egg production declines at high environmental temperatures and humidities. ASAE Paper No. 904021. St. Joseph, Mich.:ASAE.