STUDIES ON GENETICS OF HEAT STRESS IN US HOLSTEINS

by

JARMILA BOHMANOVA

(Under the Direction of Ignacy Misztal)

ABSTRACT

The objective of this study was to explore the genetic component of heat stress in U.S. Holsteins using national milk yield data consisting of 57 million first-parity test-day records of 6 million Holstein cows that calved from 1993 through 2004 and weather records from 202 public weather stations.

Seven temperature humidity indices were compared in a humid and semi-arid climate for their ability to detect a decline of milk yield due to heat stress. The index with a higher weight on humidity was the best in the humid climate. The index with a larger weight on temperature was the best heat stress indicator in the semi-arid climate.

National genetic evaluation for heat tolerance was conducted using a repeatability test-day model. Based on estimated heat tolerance PTAs, the 100 most and 100 least heat-tolerant sires were selected. For each of the 200 sires, official U.S. PTAs from February 2006 were obtained. Sires that were the most heat tolerant transmitted lower milk yields with higher fat and protein contents than did sires that were the least heat tolerant. Daughters of the most heat tolerant sires had better udder and body composition, better type, lower dairy form, slightly higher TPI, longer productive life, higher daughter pregnancy rate, were easier calving and had better persistency than did daughters of the least heat tolerant sires.

Heat stress was evaluated as a factor in the genotype x environment interaction on milk production in the United States. Data for the Southeast and Northeast were extracted from the national data set and analyzed separately. Two repeatability models with and without the effect of heat stress were implemented. Both models were fitted with the national and regional data sets. Correlations between breeding values of sires with ≥ 100 and ≥ 300 daughters in two regions were calculated. When heat stress was ignored (first model), the correlation of regular breeding values between regions for sires with ≥ 100 (≥ 300) daughters was 0.85 (0.87). Heat stress as modeled here explains only a small amount of genotype by environment interaction, partly because test day records provide only snapshots of heat stress over a hot season.

INDEX WORDS: Dairy cattle, Genetic evaluation, Genotype by environment interaction, Holstein, Heat stress, Milk yield, Temperature humidity index

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M.S., Czech University of Agriculture, Czech Republic, 2001

A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial

Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2006

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May 2006

ACKNOWLEDGEMENTS

I would like to express my deepest gratitude to Dr. Ignacy Misztal for his critical guidance and invaluable assistance. It has been a pleasure and honor to work with him during the course of my programs. Many thanks must also go to members of my committee; Drs. Romdhane Rekaya, Keith Bertrand, Joe West and Gerrit Hoogenboom for their advice and assistance.

I wish to thank the past and current members of Animal Breeding and Genetics group at UGA for providing friendly and enthusiastic environment. In particular, I would like to thank Drs. Shogo Tsuruta, Jesus Arango, Saidu Oseni, Andres Legarra, Kath Donoghue, and Robyn Sapp for their friendship and assistance. Special thanks must go to Brenda Burke for her friendship, encouragement and teaching me ‘the correct way of talking’. I also want to thank Mike Kelley for his technical support over the years. It has been a pleasure to spend time with such a wonderful group of people.

The friendship and assistance of Carolina Realini, Jorge Urioste, Ignacio Aguilar and Mary Orwig is greatly appreciated. Conversations with Drs. Tom Lawlor, John Cole and Dean Roger have been beneficial and enjoyable.

I would like to thank my friends in the Czech Republic for their encouragement and stimulation. Finally, special thanks must go to my parents, brother and his wife and my grandparents for their invaluable and unconditional love, support and encouragement.

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CHAPTER 1

INTRODUCTION

Heat stress is one of the major factors that has a negative impact on milk production and reproduction of Holstein cattle in the southern part of United States. The impact of heat stress can be relieved by modification of the environment (nutrition, cooling) or by genetic selection of animals less affected by thermal stress. Identification of such animals can be based on measurements of their immediate response (rectal, skin, milk temperature, respiration rate) to the exposure to heat stress conditions. However, it is impossible to use these variables in a breeding program because the collecting of such records on a national basis would be very tedious and labor intensive. Alternatively, a decline of production due to heat stress can be used as an indicator of heat tolerance. In Holsteins, test-day milk yield is an obvious choice. The animal with a minimal decline of milk production per degree of increase of a climatic variable is identified as heat tolerant. Dry bulb temperatures combined with humidity in an index are usually used for the description of climatic conditions because of their availability from public weather stations. Meteorological data from public weather stations provide an accurate description of environmental conditions on farms even kilometers away. Nevertheless, if cooling devices are used on the farm, the actual climatic conditions in the barn are different from those at the weather station. This fact can significantly mask the real effect of heat stress. However, accounting for the effect of cooling is compromised by a lack of adequate records on the use and efficiency of these heat abatement devices.

The first objective of this study was to identify the best temperature humidity index suitable for studying heat stress in Holsteins. Currently seven different indices are available but none of them was specifically designed for Holstein cattle. The second objective was to conduct a genetic evaluation for heat stress and identify genetically superior sires for heat tolerance and investigate their genetic value in yield and non-yield traits. The third objective was to investigate whether heat stress is a factor in the genotype by environment interaction for milk production in the United States.

CHAPTER 2

REVIEW OF LITERATURE

Cattle, as other homeothermic animals, require relatively constant core body temperature for their vital and productive processes. The body temperature of homeothermic animals is relatively uniform, fluctuating around 39°C. But since extensive metabolic heat is produced by internal organs, the core is usually warmer than the shell. Body temperature also varies with the time of the day, tending to be lower in the morning and higher in the late afternoon and early evening. Diurnal variation of body temperature doesn't exceed 1°C if the animal is exposed to a natural environment. The highest increase of body temperature occurs after feeding (Yousef, 1985). In cows, body temperature varies with the stage of lactation, level of milk production, physical activity and stage of the estrous cycle (Curtis, 1983; Shearer and Beede, 1990b).

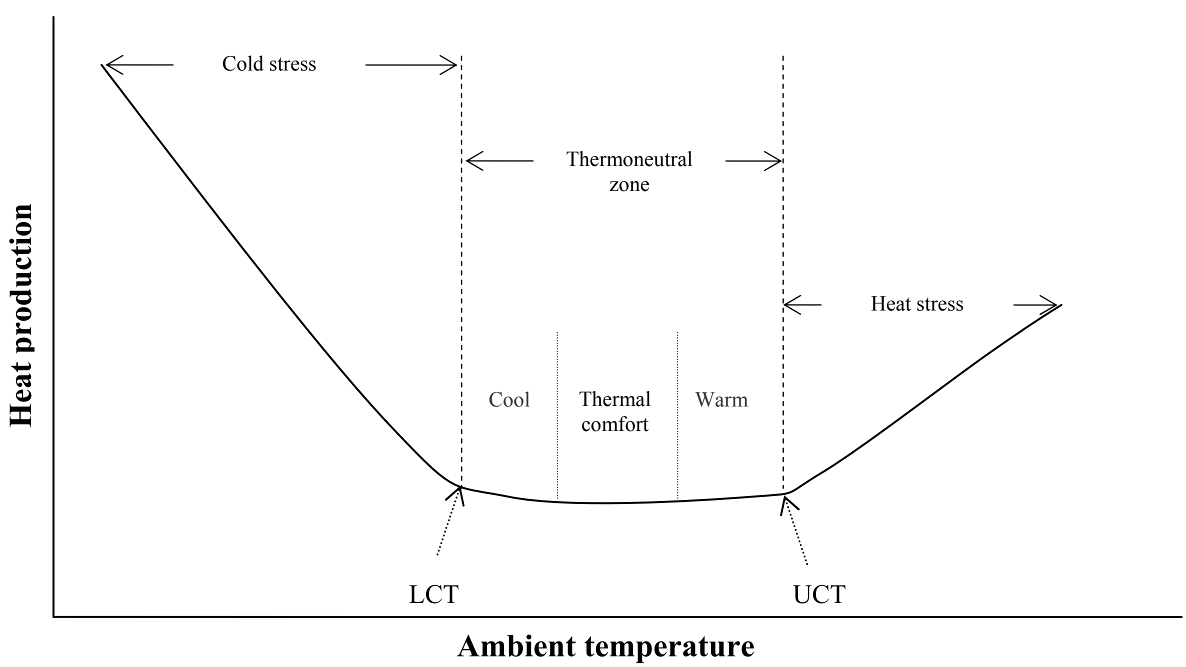
The best single indicator of average body temperature is probably blood temperature in the aorta since it represents a mixture of blood from all over the body. Rectal temperature estimates average body temperature less accurately because it changes more slowly than average body temperature (Curtis, 1983). Igono et al. (1987) reported that milk temperature is a practical measurement for assessment of heat stress in dairy cattle.

Thermoneutral zone

Thermoneutral zone (comfort zone) is the range of ambient temperature within which metabolic rate is at a minimum, and within which temperature regulation is achieved by nonevaporative physical processes alone. The most comfortable range of environmental temperatures for milk production of dairy cattle is between 0 and 16°C (Yousef, 1985).

As shown in Figure 2.1, the thermoneutral zone is bounded by the lower critical temperature (LCT), which is defined as the ambient temperature below which the rate of metabolic heat production increases by shivering and (or) nonshivering thermogenic processes to maintain thermal balance. The upper end of the thermoneutral zone, at which the increase in heat production is primarily due to a rise in body temperature, is called the upper critical temperature (UCT). The UCT is also defined as the ambient temperature above which thermoregulatory evaporative heat loss processes are activated (Yousef, 1985).

Figure 2.1: Diagram of the relationship between ambient temperature and heat production (adapted from Yousef (1985) and Curtis (1981))



The thermoneutral zone is subdivided into three subzones: cool, thermal comfort, and warm. The cool zone is the range of ambient temperature where heat production remains minimal and the animal conserves energy by cover insulation (piloerection), tissue insulation (peripheral vasoconstriction) and cold induced heat production (shivering). The thermal comfort zone is the range of ambient temperature where optimum productivity, efficiency, and performance is demonstrated. The warm zone is the range of ambient temperature where heat production is minimal, and the thermoregulatory responses are limited to decreasing tissue insulation by vasodilatation and increasing the effective surface area by changing posture (Curtis, 1983; Yousef, 1985).

The lower critical temperature (LCT) varies and dependends upon age, nutrition, level of production, specific housing and pen conditions, breed type, behavior, and acclimatization. Upper critical temperature is less variable and depends on the degree of acclimatization, rate of production, pregnancy status, air movement around animals, and relative humidity (Fuquay, 1981; Shearer and Beede, 1990a; Young, 1981).

When ambient temperature rises above *the upper critical temperature (UCT)*, the animal can no longer control its body temperature, and the hypothalamic thermoregulatory center sends signals to induce a sequence of thermoregulatory responses increasing peripheral blood flow from internal organs to peripheral tissues, sweating, and panting, reducing feed intake and nutrient absorption (Shearer and Beede, 1990b). The active dissipation processes (sweating and panting) require the expenditure of considerable amount of energy, hence in the heat stress zone the animal's heat production rises above the minimal level (Curtis, 1983).

Defining heat stress

Stress denotes the magnitude of external forces which tend to displace the bodily system from its resting or ground state (Yousef, 1985). Stress may be climatic, such as extensive cold or heat; nutritional, due to feed or water deprivation; social, resulting from a low rank in the pecking order or internal, due to some physiological disorder, pathogens or toxins (Stott, 1981). *Strain* is described as the displacement from the resting or ground state by internal forces (Yousef, 1985). *Heat stress* occurs when any combination of environmental factors cause the effective temperature of the environment to be higher than the animal's thermoneutral zone (Armstrong, 1994). Stress from the thermal environment is a major factor negatively affecting production and reproduction of dairy cattle. Annual economic losses of the US dairy industries caused by heat stress average $897 million (St-Pierre et al., 2003). Because of the major significance of this problem, heat stress in dairy cattle has been extensively discussed by many authors (Bianca, 1965; Garcia-Ispierto et al., 2006; Kadzere et al., 2002; Nienaber et al., 1999; Shearer and Beede, 1990a; Shearer and Beede, 1990b; St-Pierre et al., 2003; West, 2003; Yousef, 1985) in the last several decades.

Response to heat stress

Adaptation is a change which reduces the physiological strain produced by a stressful component of the total environment. Two types of adaptations are recognized:

1. Genetic adaptation – a genetically fixed condition of a specie, which favors survival in a particular environment
2. Phenotypic adaptation - an adaptation occurring within the lifetime of the organism

Acclimation is a short term physiological change, occurring within the lifetime of an organism due to experimentally induced stressful changes, in particular, climatic factors.

Acclimatization is a short term, usually seasonal, physiological change, occurring within the lifetime of an organism, caused by stressful changes in the natural climate (Yousef, 1985).

Hardening is a short term process induced by extreme but non-lethal stress conditions. The changes brought about by hardening are reversible, whereas acclimation leads to irreversible changes. These changes affect fitness traits such as fecundity and longevity and stress resistance (Jakobsen et al., 2002).

Heat exchange

Heat stress occurs when the sum of metabolic heat and heat received from the environment exceeds heat dissipated. Metabolic heat includes the energy necessary for maintenance plus increments for exercise, growth, lactation, gestation and feeding (Fuquay, 1981).

Thermal exchange between animal and environment are via radiation, convection and conduction and evaporation. The rate of exchange depends on the ability of the environment to accept heat and vapor. Evaporation and condensation occur along a vapor gradient (difference between the animal surface and environmental vapor pressure). Resistance to nonevaporative heat transfer is proportional to the temperature gradients within the animal and between it and the environment.

Solar radiation

Solar radiation is the radiant energy from the sun. The heat load on cow bodies from solar radiation is produced by absorption of light and associated heat on the surface of animals exposed to sunlight (Becerril et al., 1993). During the day, heat gain from solar radiation and metabolism usually exceeds heat loss from radiation, convection and evaporation, so that some heat is stored and body temperature rises. At night, the heat flow reverses and stored heat is dissipated back to the environment and body temperature falls (Finch, 1986). Radiation is an important avenue of heat loss whenever all or part of the surrounding is cooler than the animal's surface. It is of major importance at night when the animal radiates to the cooler sky. High humidity and clouds impede cooling by radiation (Fuquay, 1981). The amount of heat absorbed by an animal exposed to direct sunlight is related to coat color. Black cows absorb over twice as much heat from the sun as white cows (Shearer and Beede, 1990b).

Convection and Conduction

Heat is gained from the environment by convection or conduction only if air temperature is higher than skin temperature or if the animal is resting against a surface hotter than its skin (Fuquay, 1981). The nature of the floor determines the rate at which animals lose heat to the floor. Conductive heat loss ordinarily comprises a relatively small portion of total heat loss, ranging from 10 - 15% (Curtis, 1983).

Evaporative heat loss

Evaporative heat loss occurs when the dew point temperature of the air around the animal is lower than the temperature of the evaporative surfaces of the animal. Increased air velocity around the animal and low humidity facilitates evaporative heat loss. As the ambient temperature rises, evaporative heat loss becomes the major avenue of heat loss because it is not dependent on the thermal gradient, as are conduction and convection (Fuquay, 1981). At the air temperature of 40 °C, approximately 84% of the total evaporative heat loss is by means of sweating (Yousef, 1985).

Physiological responses of exposure to thermal stress

Temperatures above the thermoneutral zone trigger a chain of physiological, anatomical and behavioral changes in the animal's body, such as reduction of feed intake, decline of performance (milk production, growth, and reproduction), decrease of activity, increase of respiratory rate and body temperature, increase of peripheral blood flow and sweating and change in endocrine function.

Reduced feed intake

Thermal stress affects the dynamic characteristics of digestion and neuroendocrine factors influencing digestion. Declining feed intake has been identified as a major cause of reduced milk production in dairy cows. Also, a reduction in the efficiency of converting feed energy units to production energy units during heat stress has been reported (Fuquay, 1981). Maust et al. (1972) reported a negative correlation between rectal temperature and feed intake on the same day. This suggests that elevated body temperature influences feed intake. Ominski et al. (2002) observed a 6.5% decrease of feed intake after short term heat stress. During the recuperation phase dry matter intake (DMI) remained depressed which indicates that the recovery from heat stress is not immediate. In the experiment of Holter et al. (1996), DMI of Jersey cows was depressed by 17% when the minimum temperature humidity index exceeded 59. Bouraoui et al.(2002) found a 9.6% decrease in DMI when the temperature humidity index increased from 69 to 78.

Decreased milk production

Reduced milk yield under heat stress is caused by associated effects on thermal regulation, energy balance and endocrine changes (Yousef, 1985). In the study of Ominski et al. (2002), milk production decreased by 4.8 % when cows were exposed to heat stress compared to milk production of cows in the thermoneutral zone. Bouraoui et al.(2002) reported a decrease of milk production by 0.4 kg for every degree above temperature humidity index of 69. West et al. (2003) found a linear relationship between temperature humidity index and milk production. The decline of milk production per degree of temperature humidity index two days prior milk recording was 0.88 kg and 0.69 kg for Holstein and Jersey cows, respectively.

Decreased reproduction

Heat stress dramatically lowers conception rates, influences estrus behavior, modifies endocrine function, alters the oviductal and uterine environments, and delays or interrupts early embryo development of dairy cattle. The most common causes of reproductive inefficiency in dairy herds are inadequate estrus detection, absence of expressed estrus and infertility, some of which is due to embryonic mortality. Because the early embryo is the most susceptible to heat stress, the incorporation of cooling strategies for cows on the day of estrus and for 7 days thereafter would most likely decrease embryo loss due to hyperthermia. Heat stress does not prevent the occurrence of normal estrus cycles. It does, however, amplify the problem of heat detection by reducing the length of the estrus period, from 18 hours down to about 10 hours, and lowering the intensity of estrus behavior (Shearer and Beede, 1990a).

The dominance of the large follicle is suppressed during heat stress, and the steroidogenic capacity of theca and granulose cells is also compromised. Heat stress impairs oocyte quality and embryo development, and increases embryo mortality. In addition to the immediate effects, delayed effects of heat stress have been detected as well. Conception rates drop from about 40–60% in cooler months to 10–20% or lower in summer (Wolfenson et al., 2000).

Continuous exposure of bulls to temperatures > 29.4°C decreases sperm concentration, lower motility, and increases the percentages of morphologically abnormal sperm (Ax et al., 1987). Ravagnolo and Misztal (2002a) reported using a two trait model for nonreturn rate at 90 days (NR90) and test-day milk yield, correlation of -0.35 between NR90 and THI, suggesting negative relationship between heat tolerance and reproduction. In the following study

(Ravagnolo and Misztal, 2002b), nonreturn rates at 45 days (NR45) of first parity cows were more sensitive to THI above 70 than NR45 of cows in later parities. The THI on the day of insemination showed the highest effect on NR45.

Increased water intake

Water consumption of dairy cattle is increased in order to compensate for losses of water from evaporative heat loss through sweating and panting during the period of heat stress. Since sweat of ruminants is high in K, cows also have to compensate for large loses of K in sweat (Shearer and Beede, 1990b).

Changed metabolic rate and maintenance requirements

McDowell et al. (1969) noted a twofold higher decline of milk energy output than decline of digestible energy intake in Holstein cows, resulting in a marked decrease in efficiency of the utilization of energy. The increase in the energy requirement under heat stress is caused by increased blood transport, increased action of the sweat glands and metabolic rate coping with elevated body temperature.

Increased respiration rate

McDowell et al. (1969) observed respiration rate of Holstein cows during a two weeks exposure to heat stress. The highest respiratory rates were recorded on the first and second day, with a plateau period through the fourth day, followed by a gradual decline through the second week. Respiration rate returned to the initial level in 8 hours after removal from heat stress.

Changed blood hormone concentration

Secretion of hormones associated with metabolism (thyroxine, somatotropine, and glucocoritcoids) and water balance (antidiureteic hormone and aldosterone) are significantly influenced by heat stress. Several days after heat stress begins, the secretion rate of thyriod hormones is reduced. Growth hormone secretion rates are reduced during prolonged heat stress after initial rise (Curtis, 1983). Adrenal corticoids, mainly cortisol, elicit physiological adjustments that enable animals to tolerate stressful conditions. However, the effects of high temperatures on cortisol levels are inconsistent (Correa-Calderon et al., 2004).

Climatic heat stress factors

The main factors which are responsible for energy flow to the animal are: effective air temperature, solar radiation, relative humidity, wind speed and structural properties of animal's coat (Yousef, 1985). Thermal environment can be represented by a single or a combination of the bioclimatic factors. Extensive efforts have been undertaken to develop an index to take into account all environmental factors (ambient temperature, relative humidity, solar radiation and wind speed) causing measurable physiological responses.

Wet-bulb globe temperature is an index developed for humans and is calculated as:

$$WBGT = (0.7 \times T_{wb}) + (0.2 \times T_{gl}) + (0.1 \times T_{db})$$

where T_{wb} is a wet bulb temperature, T_{gl} is a globe temperature, T_{db} is a dry bulb temperature (Yousef, 1985). All T values are in °C.

Temperature-humidity index (THI) is an index developed to assess discomfort related to high ambient temperature and relative humidity. Animal species differ in sensitivity to ambient temperature and vapor pressure. This fact is considered by specific weightings given to dry and wet bulb air temperatures in THI for different species. The index for cattle is estimated as: THI =

$(0.35 \times T_{db} + 0.65 \times T_{wb}) \times 1.8 + 32$. The formula for young pigs is: THI = $(0.65 \times T_{db} + 0.35 \times T_{wb}) \times 1.8 + 32$. The THI for man is expressed as: THI = $(0.15 \times T_{db} + 0.85 \times T_{wb}) \times 1.8 + 32$. (National Research Council, 1971).

National Research Council (1971) empirically determined indices weighting dry bulb and wet bulb or dew point temperatures (T_{dp}), and relative humidity (RH):

THI = $[0.4 \times (T_{db} + T_{wb}) + 15] \times 1.8 + 32$

THI = $[0.55 \times T_{db} + 0.2 \times T_{dp}] \times 1.8 + 32 + 17.5$

THI = $(1.8 \times T_{db} + 32) - (0.55 - 0.55 \times RH) \times (1.8 \times T_{db} - 26)$

Temperature-humidity index developed by the U.S. National Weather Service in 1959 for man has the following form: THI = $(T_{db} + T_{wb}) \times 0.72 + 40.6$. Yousef (1985) based his temperature-humidity index on combination of dry bulb temperature and dew point temperature (Tdp): THI = $T_{db} + 0.36 \times T_{dp} + 41.2$

Ravagnolo et al. (2000) compared different environmental factors (average, minimal, maximal temperature, relative humidity, THI) for prediction of a depressing effect of heat stress on milk production. The factor with the greatest influence on milk production was THI. Milk production decreased by 0.2 kg per unit of THI > 72.

West et al (2003) tested effects of different weather variables (minimum, maximum, and mean air temperature, relative humidity and THI) obtained at the day of recording, one, two or three days before the record was taken on milk production of Holstein and Jersey cows. The variable that had the greatest impact on milk production was mean THI two days before (THI2-d). The importance of the two day lag between the time of exposure and response of the animal can be explained by the time required to consume, digest and utilize consumed nutrients. Using

THI2-d, the decline in milk production was -0.88 kg/unit THI for Holsteins and -0.60 kg unit THI for Jerseys.

Holter et al. (1996) noted that daily minimum THI is a better environmental indicator for the prediction of dry matter intake than daily maximum THI. St-Pierre et al. (2003) declared THI of 70, 77 and 72 to be the degrees at which heat stress begins in dairy cows, dairy heifers (0 to 1 year) and dairy heifers (1 to 2 years), respectively. Igono et al. (1992) determined the critical values for minimum, mean and maximum THI in Holstein cows to be 64, 72 and 76, respectively.

Temperature humidity index is used to evaluate impact of heat stress on the production of livestock all over the world (Aharoni et al., 2002; Bouraoui et al., 2002; Correa-Calderon et al., 2004; Finocchiaro et al., 2005; Holter et al., 1997; Holter et al., 1996; Igono and Johnson, 1990; Igono et al., 1985; Ravagnolo and Misztal, 2000; Ravagnolo and Misztal, 2002a; Ravagnolo and Misztal, 2002b; Ravagnolo et al., 2000; Rodriquez et al., 1985; St-Pierre et al., 2003; West et al., 2003).

Equivalent temperature incorporates dry bulb temperature, relative humidity and solar radiation. The disadvantage of this measure lies in the difficulty of obtaining a suitable evaluation of the amount of thermal radiation received by an animal (Silanikove, 2000).

Black globe temperature combines the effects of total incoming radiation from the sun, horizon, ground and other subjects with air temperature and wind speed (Silanikove, 2000). Araki (1985) used black globe temperature to estimate the effect of sprinkler and fan cooling on vaginal temperature patterns of Holstein cows.

Black globe humidity index is a combination of black globe temperature with wet bulb temperature. It is one of the best indices to represent heat stress in open areas; nevertheless, it accounted for only 24 % of the variance of heat stress-related milk yield depression in dairy cows (Silanikove, 2000).

Factors influencing heat tolerance

Level of milk production

Total body heat load of lactating cows is elevated by a rise in the metabolic heat associated with milk production, which aggravates her ability to maintain homeothermy under conditions of heat stress. Therefore, lactating animals, and especially higher producing and multiparous cows, are more sensitive to heat stress than non-lactating animals (Bianca, 1965). Fuquay et al. (1981) reported that for each 0.45 kg of milk, a 454 kg cow produces 10 kcal of metabolic heat per hour.

Stage of lactation

Maust et al. (1972) investigated effects of heat stress on energy intake, milk yield, milk fat and rectal temperature of 36 Holstein cows representing three stages of lactation: early lactation (below 100 days in milk), mid-lactation (from 100 to 180 days) and late lactation (from 180 to 360 days). Cows in the early stage of lactation extensively utilize body reserves and are less dependent on consumed feed energy. They were the highest in production, despite of consuming the least feed. Mid-lactation cows were most adversely influenced by heat stress; late intermediately, and early lactation the least. Cows in mid-lactation were most affected, but they seemed to recover from one or more days of thermal stress better than cows in late lactation.

Length of exposure to heat stress

Effects of length of thermal stress on gross efficiency (kg milk/Mcal ENE) has been examined by McDowel et al. (1976). Authors reported 27% higher gross efficiency in cows exposed to 20 days of maximum temperature above 27°C compared to cows exposed to the same conditions for 40 to 80 days. Igono and Johnson (1990) observed a decline in milk production when the animal's rectal temperature was > 39°C for more than16 hours.

Nutrition

Food intake is related directly to all aspects of energy metabolism with the release of heat for maintenance, activities and production. Changes in the quality or quantity of food alters the intensity of the metabolic heat load (Finch, 1986). Chen (1993) investigated the effect of supplemental protein quality on dairy cows exposed to thermal stress. Milk yield was higher by 11% for cows fed high than for cows fed low quality protein. Dry matter intake, respiration rate and rectal temperature were not affected by the quality of protein.

Bovine somatotropin (bST) treatment

Elvinger et al. (1992) observed an effect of bST on cows in thermoregulated and heat stress environments. The authors found higher rectal temperatures for cows treated with bST than cows treated with placebo. Cows administered bST had higher milk yield in both environments. Respiration rate of heat stressed cows was not affected by bST.

Cows that were administered bST were affected by thermal stress as were other high producing cows if excessive metabolic heat was not dissipated. The use of bST does not change the maintance requirement or partial efficiencies of milk yield (West, 1994). The effect of bST is maximized when the animal's internal temperature stays in the thermoneutral zone (Keister et al., 2002), indicating that cows administered by bST in the hot season have to be cooled by heat abatement devices.

Differences in heat tolerance between cattle species

Many authors have provided evidence of *Bos indicus* cattle being more heat tolerant than *Bos taurus*. The sweat glands are larger and closer to the skin surface in *Bos indicus* than in *Bos taurus*. Also, the density of sweat gland population is higher. Although *Bos indicus* has larger and more sweat glands, it has only slightly higher sweating rates than *Bos taurus* under comparable conditions of heat stress. In *Bos indicus*, sweating rates increase exponentially in response to increases in body temperature, while in *Bos taurus* sweating rates tend to plateau after an initial increase.

There is a noticeable difference between the species in their ability to regulate rectal temperature. The mean rectal temperature of heat stressed animals is higher in *Bos taurus* than in *Bos indicus* and as a result the total depression in fertility is much larger in *Bos taurus* than in *Bos indicus* (Curtis, 1983). Better heat tolerance of *Bos indicus* cattle is mainly due to greater surface area, particularly in the region of the dewlap and prepuce, larger number of sweat glands, and short hair. Furthermore, lighter coat colors and the distribution of fat such as intramuscular or fat in the hump assists in heat loss from the core (Yousef, 1985).

Differences between breeds

Although animals of all breeds respond to chronic exposure to heat stress by a decrease in their production, the environmental temperature at which this decrease begins varies considerably. The upper critical temperature for milk production of Holsteins is 21°C and is slightly higher in Jersey and Brown Swiss (24°C) and considerably higher in Brahman cows

(35°C). Lower producing, tropically evolved cattle or tropically adapted Criolla and native cattle appear to decrease milk yield in around 29°C (Yousef, 1985).

Srikandakumar and Johnson (2004) reported a higher rectal temperature of Holstein cows (39.2°C) than that of both Jersey (38.7°C) and Australian Milking Zebu (38.8°C) cows in December (summer in Australia). Higher rectal temperatures in Holstein cows were explained by higher heat production. However, the magnitude of the increase in rectal temperature during heat stress was lowest in Australian Milking Zebu cows (0.38°C) followed by Holstein (0.47°C) and Jersey cows (0.70°C). The Jersey cows thus appear to be the least capable in maintaining their normal body temperature.

West et al. (2003) reported higher milk temperature in Holsteins cows (39.3°C) than Jersey cows (39.1°C) in summer months in Georgia. Similarly as in the previous study, the magnitude of increase in milk temperature was higher in Jersey cows (0.6°C) compared to Holstein cows (0.5°C). The Jersey breed has become a popular choice of farmers from regions significantly affected by heat stress. Keister et al. (2002) reported that Jersey cow numbers increased in Arizona from 2.5% of the cows in 1975 to 13.4% in 2000. This is mainly due to the fact that milk production and reproduction of Jersey cows is not as depressed as in Holstein cows during thermal stress.

Structure and color of animal's coat

There is a significant effect of coat color on heat exchanges within the coat. The differences in heat load due to color become important to thermoregulation if water is limited. Animals with dark coats become more rapidly dehydrated and their body temperatures rise more rapidly than those of light colored coats (Finch, 1986).

Becerril et al. (1993) found a significant effect of white coat color percentage on milk production, fat and protein percentages of first lactation Holstein cows. Milk production increased by 1.91 kg per 1% increase in white color. Heritability of percentage of white color was 0.72 using an animal model (Becerril et al., 1994) and 0.22 using a paternal half-sib analysis (King et al., 1988).

Size of the animal

In a hot environment a small animal has a thermoregulatory advantage over a large but otherwise similar animal, because of its greater surface area per unit of body mass. For the same reason, a slender animal with large body appendages, such as the dewlap and ears, has an advantage over a compact animal with small appendages but with otherwise similar features. In some of the tropical regions small cattle may be found, not because they are more efficient in their heat dissipation but because they are more resistant to certain diseases and to a low standard of nutrition (Bianca, 1965).

The number of sweat glands corresponds to the number of hair follicles and is fixed at birth. Thus, with increasing size of the animal, the number of sweat glands per unit area of skin decreases. More important than the number of sweat glands seams to be their volume. There is evidence that high sweat-gland volumes are associated with high heat tolerance (Bianca, 1965).

Acclimatization

Acclimatization to heat stress occurs when an animal, in response to repeated or continuous exposure to an environment hotter than formerly experienced, develops functional, structural, and behavioral traits that increase its ability to live in a hot environment without distress (Curtis, 1983). Animals become adapted to summer heat by changes in hair coat and by reducing their resting metabolic rate. Rearing calves in a warm environment (27°C) improves their later heat tolerance, whereas rearing them in a cool environment (10°C) improves their later cold tolerance. Since the heat acclimatized animals become more sensitive to cold and the cold-acclimatized animals more sensitive to heat, this also meant that the whole zone of thermoneutrality had been shifted, upwards in the heat tolerant group and downwards in the other (Bianca, 1965). In Canada and the Northern United States, animals are exposed to mild or moderate short-term heat stress. Thermal heat stress in these temperate regions poses a serious problem because animals have not adapted physiologically to the heat stress conditions (Ominski et al., 2002).

Day length

Barash et al. (2001) studied a combined effect of the temperature and day length on milk production of Holstein cows. They reported that milk production was reduced by 0.01 kg/°C and elongation of day length by 1 hour increased milk production by 1.2 kg. Aharoni et al. (2002) found a positive effect of pre-partum short days on milk yield.

Methods for assessment of heat tolerance

It is difficult to define heat stress because the response to thermal stressors is a complex reaction. Different methods have been developed to identify heat tolerant animals.

Rectal temperature (T_{rec}) is the most widely used measure to determine an animal's heat tolerance, which is expressed as an increase of T_{rec} above a level of 38.3°C (Bianca, 1965; Igono and Johnson, 1990). However, use of T_{rec} for detection of acute heat stress is limited because of its lag in response to rising ambient temperature. Moreover, T_{rec} is prone to errors from sources such as variability in depth and duration of probe insertion, as well as variation in animal handing (West et al., 2003).

Stress degree hours denote the number of hours per day when T_{rec} is greater than 39°C. T_{rec} of 39°C is taken as the critical value because at this temperature thermoregulatory and productive functions of the cow are adversely affected. A high magnitude of stress degree hours indicates inability of heat dissipating mechanism to cope with the animal's heat load in terms of combined effects of intensity and duration of thermal stress (Igono and Johnson, 1990).

Milk temperature is a popular indicator of heat stress in dairy cows. West et al. (2003) used milk temperature to monitor body temperature of cows in summer months in Georgia. Authors found that dry matter intake and milk production followed a curvilinear relationship with milk temperature. Further, milk temperature increased linearly with increasing ambient temperature. West et al. (1990) found a correlation of 0.87 and 0.89 between p.m. milk and rectal temperatures for shaded cows and for cows with shade, spray and fans, respectively. Igono et al. (1985) studied the benefits of spray cooling on cows comfort. Responses of lactating Holstein and Guernsey cows were measured by milk and rectal temperature. Authors reported that milk temperature provides reliable indication of heat stress comparable to rectal temperature.

Respiratory rate (RR) is easily observable by counting flank movement but for a long-term study collecting measurements becomes tedious and labor intensive. A respiration rate of 60 bpm is a normal rate, 120 bmp reflects heat stress. Cows exposed to heat stress begin to rise in RR in significantly lower air temperatures than for rectal temperature (Bianca, 1965).

Skin temperature was lowly correlated with rectal temperature ($r = -0.022$) and respiration rate ($r = - 0.086$) in the study of Umphrey et al. (2001), indicating that skin temperature is not a good indicator of an animal’s body temperature.

Tympanic temperature

Frequently collected data of tympanic temperature provides fine details of an animal's ability to cope with thermal stress. Hahn et al. (1992) recommended the use of a fractal analysis technique of tympanic temperature for the evaluation of heat tolerance of animals.

Heat shock proteins (Hsps)

Heat shock proteins function as molecular chaperones that help animals to cope with stress. They can be induced in addition to heat by environmental factors such as cold, heavy metals, ethanol fumes, insecticides, parasites, diseases or genetic stress (inbreeding). Hsps are primarily involved in protein quality system, they fold proteins and prevent aggregation of misfolded proteins (Sørensen et al., 2003). They are classified into 5 families according to their molecular weight (Hsp100, Hsp90, Hsp70, Hsp60 and the small Hsps). The heat shock genes are highly preserved and show low variation between species, suggesting evolutionary importance of cell protection during and after stress. Hsp expression is fine tuned (not being only an on-off mechanism) and are also continuously expressed after a mild chronic stress exposure (Hoffmann et al., 2003). To date, research has been mainly focused on the Hsp70 family. In bovines, Hsp72 has been believed to be absent under nonstressful conditions and therefore the prospect of using the Hsp 70 family as a selection criterion for heat tolerance has been discussed. However, the study of Kristensen et al. (2004) showed that Hsp72 is also present in the plasma from nonstressed Holstein dairy cattle and which eliminated this possibility.

Response functions

The level of heat stress can be measured indirectly through the response of the animals. Unfortunately, accurate estimation of this response is difficult because the magnitude of decline of production can be caused not only by climatic conditions but also by other factors, such as coat color, disease incidence, feed quality and quantity and management regime (type of cooling system, time of usage). Due to the lack of information concerning the presence of these factors, it is difficult to statistically separate these confounding factors from the real heat load effect (Mayer et al., 1999; Stott, 1981).

Hahn (1981) proposed a response function of THI on milk production, conception, rectal temperature and hay intake to predict an animal's performance at various locations in the United States. Lindvill and Pardue (1992) developed a model for the prediction of summer milk production using "total hours during the past 4 days during which THI > 74" (HD74) and "square of total hours during the past day during which THI > 80" (HA80S). HD74 described the ability of dairy cattle to acclimate to hot weather and HA80S captured extreme events.

Diurnal patterns of temperature (nighttime cooling)

The severity of heat stress depends to a large extent on the diurnal fluctuations of the ambient temperature. Kabuga (1992) observed diurnal pattern in rectal temperatures, respiratory rates and pulse rate (being lower in the morning than afternoons), suggesting that animals are able to cope with heat stress by storing heat during the day and dissipating it at night.

Nighttime environmental conditions strongly affect the thermal balance and milk yield of cows (Spain and Spiers, 2001). The effects of heat stress that may be experienced during high day ambient temperatures may be ameliorated when night temperatures fall (Akari et al., 1987).

During heat stress, the cool period of hours per day with temperature < 21°C provides a margin of safety which reduces the effects of heat stress on milk production (Igono et al., 1992). Nighttime cooling is necessary for recovery from thermal stress. Dairy cattle can recover from heat stress if nighttime temperature is below 20°C (Spiers et al., 2001). Holter et al. (1996)

reported, that daytime heat stress had a lower effect on dry matter intake (DMI) when there was at least a temporary nighttime respite. In the study of Keister et al. (2002), cows were able to maintain milk production on days with high daytime temperatures as long as night THI were below 75. However, once nighttime THI went above 75, there was a precipitous drop in daily milk production (2.8 kg) and DMI. Whenever the nighttime THI dropped below 75, there was an increase in dry matter intake the following day. Nienaber et al. (2003) reported severe heat stress when animals were exposed to THI≥ 70 over a three-day period without a significant nighttime relief.

Characteristics of a heat tolerant animal

Heat tolerance reflects the ability of an animal to maintain normal temperature with an increase in ambient temperature. In general, small animals have a thermoregulatory advantage over large animals because of their greater surface area per unit of body mass. For the same reason a slender animal with large body appendages, such as dewlap and ears, has an advantage over a compact animal with small appendages but otherwise similar features. The superiority of heat tolerance seems to be the result of a higher sweating rate and of lower heat production per unit body weight. Animals with low body temperature might have inherited low food intake and heat production regardless of the level of environmental heat stress (Bianca, 1965).

In general, the metabolic rate of heat adapted animals is lower than animals of temperate regions. Heat loss is amplified by a greater surface area, particularly in the region of the dewlap and prepuce, a larger number of sweat glands, and short hair. Furthermore, lighter coat colors and the distribution of fat such as intramuscular or fat in the hump will assist in heat loss from the core (Yousef, 1985).

Strategies for reduction of effects of heat stress

Beede and Collier (1986) suggested three strategies for alleviating the effects of heat stress:

1) physical modification of the environment (reducing incoming radiation via shade and cooling)
2) improvement of nutritional management
3) genetic development of breeds that are less sensitive to heat

1) Physical modification of the environment

Highest yields and efficiency of performance can be obtained under stable environmental conditions with temperatures in the comfort range for lactating cows. Heat stress of dairy cattle can be alleviated by different cooling systems. The degree of improvement varies with the type of system provided, climate, and production level of the cows. In many moderate climates, shade is a cost effective solution for reducing the radiation heat load of cows. Fans and sprinklers offer a practical method of alleviating heat stress during the night by increasing heat loss at the animal surface through evaporative and convective means. Cooling with evaporatively cooled air is effective in areas of low humidity. In more humid areas, this type of cooling is beneficial only in daytime hours when humidity is low enough.

Armstrong (1994) emphasized the importance of provision of cooling to cows when waiting on milking in holding pens. The holding pen is, on most dairy farms, the most stressful area for dairy cows. When a cow is confined in the holding pen for 15 to 60 minutes two or three times a day, stress can occur even under moderate ambient temperatures.

Correa-Calderon et al. (2004) investigated the effect of shade (C), spray and fan cooling (SF) and evaporative cooling system called Korral Kool (KK) on physiological responses during the summer on dairy cows in Arizona. Koral Kool is a system which injects a fine mist generated at high water pressure into a stream of air. Rectal temperature and respiration rates of cows in the C system were higher than from SF and KK.

Armstrong (1994) compared response of milk production to thermal stress in two cooling systems and found the evaporative cooling system more effective than the spray and fan system.

Effects of spray and fan in freestall areas and feeding areas on milk yield and net income in Holstein cows were studied by Igono et al. (1987). Authors found that cows cooled with sprays and fans under shade consumed more feed and produced by 2 kg more milk than cows just in a shade. Net income of spray and fan group was by $0.22/cow per day higher compared to group under shade, indicating that spray plus fan cooling is a low cost management practice that improves thermal balance, reduces declines of milk production and results in a greater profit.

Ryan et al. (1992) compared milk production, rectal temperature and reproduction (number of services, pregnancy rate) under two cooling systems: EC unit, which consisted of a large fan and nozzles which sprayed atomized water under high pressure into a dry air pushed by the fan, and SF unit, which consisted of fans hanging from the roof and spray nozzles. The mean differences in daily maximum temperature between indoors and outdoors were 18 ± 0.3°C and 9.2 ± 0.3°C for the EC and SF systems, respectively. The EC system enhanced reproduction (24% higher pregnancy rate) and milk production (by 0.9 kg) compared with the SF system. Rectal temperatures were not closely correlated with average THI for either the EC or SF cows, suggesting rectal temperature may be a poor indicator of heat load in these cooling systems. Keister et al. (2002) reported that spray and fan cooling system can lower THI by 2 degrees compared to the outside environment.

St-Pierre et al. (2003) proposed functions of temperature (T in °C) and relative humidity (RH in %) to quantify a decline in temperature-humidity index (ΔTHI) due to use of different cooling systems:

<u>Moderate heat abatement</u> - system of fans or forced ventilation

$$\Delta THI = -11.06 + (0.257 \times T) + (0.027 \times RH)$$

<u>High heat abatement</u> - combination of fans and sprinklers

$$\Delta THI = -17.6 + (0.367 \times T) + (0.047 \times RH)$$

<u>Intense heat abatement</u> - high pressure evaporative cooling system

$$\Delta THI = -11.7 + (0.16\ T) + (0.187 \times RH)$$

Authors demonstrated that for dairy cows some form of heat abatement is economically justified across all states of the United States. Total economic loses vary greatly across states due to differences in heat stress magnitude but also size of the farms in each state.

2) Improvement of nutritional management

Different feeding management strategies have been proposed to alleviate effects of heat stress. Feeding during the cooler hours of the day or at night (nighttime compensatory eating) is one technique that has been recommended by several researchers and nutritionists. Evening-fed animals are able to cool down more quickly than morning-fed cows. However, time of feeding doesn’t have any effect on the decline of milk production (Ominski et al., 2002). Another relatively simple nutritional management strategy could be to increase the number of feedings per day (Beede and Collier, 1986).

Fuquay (1981) reported that cows on a low fiber diet produced more milk and had lower rectal temperatures, respiration rates and pulse rates than cows on a high fiber diet. Knapp and Grummer (1991) studied effects of feeding supplemental long chain acids on milk production of

Holstein cows during thermal stress. Authors found no significant difference in dry mater intake, milk yield, and protein percentage between cows fed 0 or 5% supplemental fat.

3) Genetic development of heat resistant animals

Milk production of US Holstein increased by 3.500 kg during the past 20 years as a result of improved genetics, nutrition, and management (Shook, 2006). Kadzere et al. (2002) hypothesized that the thermal regulatory physiology of a cow may have been changed in response to genetic selection for increased milk production. The current high producing cows are characterized by larger frames and larger gastrointestinal tracts which allow them to consume and digest more feed but also produce more metabolic heat. Higher heat production of these cows impairs their ability to maintain normal temperature at higher ambient temperature and makes them more sensitive to heat stress. Moreover, thermoneutral zone of high producing cows is shifted to lower temperature and thus high producing cows experience heat stress earlier than low producing cows.

Little evidence is available on genes underlying heat tolerance. However, heat shock genes, have been widely discussed as candidate genes for heat resistance (Hoffmann et al., 2003).

Olson et al. (2003) reported presence of a slick hair gene in the bovine genome. This gene is dominant in mode and cattle carrying the dominant allele of this gene have slick hair and are able to maintain body temperature at lower rates. Slick hair has a positive effect on growth and milk production under dry, tropical conditions.

The phenomenon of cross resistance where exposure to one stressor enhances resistance to other stressors has been noted by Hoffmann et al. (2003). This suggests that heat stress tolerant cattle may be also tolerant to other stressors such as disease, reduced feed quality, parasites. Such stress tolerant cows may have lower culling rates and thus may stay in herds longer. This fact has been confirmed in Drosophila, where a relationship between heat resistance and longevity has been found. However, whether this is valid in cattle is unknown (Sørensen et al., 2003).

Quantitative genetic analyses of Ravagnolo and Misztal (2000) revealed a high genetic variability of milk production in Holsteins at extreme temperature and humidity, indicating the possibility for selection for heat tolerance. Authors reported a negative correlation ($r = -0.35$) between milk production in temperate and hot conditions. This fact raises a question of whether the current Holstein cow can fit all environments to which she is exposed. It may be necessary to develop strategies for selection of dairy cattle for specific climatic conditions, enabling to improve genetic potential even in warm climates. Ravagnolo and Misztal (2000) proposed a model which uses weather data from public weather stations to account for heat stress. Their model had two animal genetic effects, one corresponding to performance under mild conditions, and one corresponding to a rate of decline after crossing the threshold of heat stress. The application of this model in a genetic evaluation would predict rankings of animals in various environments with similar management but in different climatic conditions.

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CHAPTER 3

COMPARISON OF SEVEN TEMPERATURE HUMIDITY INDICES AS INDICATORS OF MILK PRODUCTION LOSSES DUE TO HEAT STRESS IN SEMI-ARID AND HUMID CLIMATES

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Abstract

Meteorological data (1993 to 2004) from two public weather stations in Phoenix, AZ and Athens, GA were analyzed with test day milk yield data from herds nearby the weather stations to identify the most appropriate temperature humidity index (THI) to measure losses in milk production due to heat stress in semi-arid climate of Arizona and humid climate of Georgia.

Seven THIs with different weightings of dry bulb temperature and humidity were compared. Test-day data were analyzed using two fixed models to determine threshold of heat stress and rate of decline of milk production identified by a specific THI. Differences in thresholds of heat stress were found among indices and between regions. The index with higher weight on humidity was the best in the humid climate, while the index with larger weighting of temperature was the best heat stress indicator in the semi-arid climate. Humidity is a more important environmental factor of heat stress in humid than in dry climates.

Introduction

Heat stress is caused by a combination of environmental factors (temperature, relative humidity, solar radiation, air movement and precipitation). Many indices combining different environmental factors have been proposed to measure the level of heat stress. However, their use is limited by availability of required data. The majority of studies on heat stress in livestock limit their attention to temperature and relative humidity, since data on amount of thermal radiation received by animal, wind speed and rainfall are not publicly available, while temperature and humidity records are usually obtained from a meteorological station located in the area.

Hubbard (1994) reported that accurate maximum temperature can be obtained from weather station in the radius of 60 km. Minimum temperature, relative humidity and solar radiation require a smaller separation distance (< 30 km).

The water vapor content of the air is an important factor because of its impact on the rate of evaporative loss through skin and lungs. Therefore as the mean daily temperature falls outside the animal's comfort zone, the amount of moisture in the air becomes a significant element in maintaining homeostasis of the animal.

Temperature humidity index (THI) is a single value representing the combined effects of air temperature and humidity associated with the level of thermal stress. This index has been developed as a weather safety index to monitor and reduce heat stress related losses. Different animal species and humans have different sensitivity to ambient temperature and amount of moisture in the air. Cattle can tolerate much higher temperature at lower relative humidity than swine. This is due to the fact that cattle can dissipate excessive heat more effectively by sweating, whereas swine do not have sweat glands. However, during hot and humid weather the natural capability of cattle to dissipate heat load by sweating and panting is compromised, and heat stress occurs at these conditions in cattle much faster than in swine (Yousef, 1985).

The water vapor content of the air may be specified in several ways. Meteorologists ordinarily use web bulb temperature (T_{wb}) because it is directly measurable. Relative humidity (RH) and dew point temperature (T_{dp}) are other alternative humidity variables.

In humans, the effect of the T_{wb} affecting her (his) comfort is almost six times as large as that of the T_{dp} while in cattle it is only about twice as large. This difference reflects differences in the capacity for evaporation. Man can dissipate by evaporation about 190% of his metabolic heat production, whereas cattle can dissipate only 105% of their metabolic heat production (Bianca, 1962).

Because of the differences in sensitivity to ambient temperature and amount of moisture in the air among species, a range of equations for calculation of THI with different weightings of dry T_{db} and air moisture has been proposed. Some indices integrate air moisture in the index by T_{wb} [3.1, 3.2, 3.3 and 3.6], others use T_{dp} [3.4, 3.7] or RH [3.5].

However, none of the indices has been designed specifically for Holstein cows milking in field conditions.

Temperature humidity index

$THI1 = (0.15 \times T_{db} + 0.85 \times T_{wb}) \times 1.8 + 32$ **[3.1]** (Bianca,1962)

$THI2 = (0.35 \times T_{db} + 0.65 \times T_{wb}) \times 1.8 + 32$ **[3.2]** (Bianca,1962)

$THI3 = [0.4 \times (T_{db} + T_{wb})] \times 1.8 + 32 + 15$ **[3.3]** (Thom, 1959)

$THI4 = (0.55 \times T_{db} + 0.2 \times T_{dp}) \times 1.8 + 32 + 17.5$ **[3.4]** (National Research Council, 1971)

$THI5 = (1.8 \times T_{db} + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26) =$ **[3.5]**

$0.81 \times T_{db} + 0.143 \times RH + 0.0099 \times RH \times T_{db} + 46.3$ (National Research Council, 1971)

$THI6 = (T_{db} + T_{wb}) \times 0.72 + 40.6$ **[3.6]** (National Research Council, 1971)

$THI7 = T_{db} + 0.36 \times T_{dp} + 41.2$ **[3.7]** (Yousef, 1985)

THI1 is an index used to monitor discomfort from temperature and humidity in humans. THI2 and THI7 have been empirically determined in cattle exposed to heat stress conditions in climatic chambers. How these indices from controlled environments relate to field conditions with diurnal fluctuation of environmental variables remains unanswered. THI3 is another index defined to monitor the degree of discomfort in people. THI5 represents the “Oklahoma Mesonet Cattle Heat Stress Index”, designed to indicate level of heat stress of outdoor cattle. THI6 has been developed by the United States Weather Bureau to describe discomfort in man.

THI is usually classified into classes which indicate level of heat stress. However, definitions of those levels vary between indices and authors. For instance, Armstrong (1994) identified index below 71 as “comfort zone”, values ranging from 72-79 as “mild stress”, 80-89 "moderate stress" and values above 90 as "severe stress". Huhnke et al. (2001) divided THI7 into two categories: 79 ≤ THI7 ≤ 83 "dangerous situation", and THI7 ≥ 84 "emergency situation". Thom (1959) categorized THI as 70 ≤ THI3 ≤ 74 "uncomfortable", 75 ≤ THI3 ≤ 79 "very uncomfortable", THI3 ≥ 80 "serious discomfort" (Thom, 1959).

The ratio of T_{wb} to T_{db} can provide a useful perspective on weighting placed on humidity and ambient temperature. The highest ratio of T_{wb} to T_{db} was for THI1 and THI2 and it is 5.7 and 1.9, respectively. The same ratio for THI3 and THI6 is 1. For THI4, THI5 and THI7, the ratio between T_{wb} and T_{db} was determined numerically and is 1.2, 0.3 and 1.2, respectively.

As mentioned earlier, humidity can be expressed by a variety of variables such as dew point temperature, wet bulb temperature and relative humidity. The following section illustrates how to translate RH into T_{dp} and T_{wb}.

Dew point temperature (T_{dp})

Dew point temperature is the temperature to which air must be cooled for saturation to occur. In simple words, it is the temperature at which relative humidity is 100 %. High dew point temperature indicates high vapor content and vice versa. Dew point temperature is a good predictor of the minimum overnight temperature, provided no fronts or other weather pattern changes are expected. When the dew-point falls below freezing it is called the *frost point*. Generally, higher dew point temperatures during periods of warm or hot weather will indicate a greater likelihood of discomfort because the air is near saturation and therefore less capable of absorbing moisture from the surface of one's skin.

Dew point temperature can be calculated as follows:

$$T_{dp} = \frac{116.9 + 237.3 \times ln(e)}{16.78 - ln(e)};\ ^{\circ}C$$ **[3.8]** (Jensen et al., 1990)

where *e* is the *ambient vapor pressure* and can be expressed as:

$$e = \frac{rh}{100} \times 0.611 \times e^{\frac{17.27 \times T_{db}}{T_{db}+237.3}};\ kPa$$ **[3.9]** (Jensen et al., 1990)

Wet bulb temperature (T_{wb})

Wet bulb temperature represents the equilibrium temperature of a thermometer covered with a cloth that has been wetted with pure water in air moving at least 4.6 m s^{-1} . When the thermometer is exposed to unsaturated air, its temperature is below the dry bulb temperature because of evaporative loss of energy. Wet bulb temperature is the lowest temperature to which air can be cooled by evaporation.

$$T_{wb} = \frac{(\gamma \times T_{db}) \times (\Delta \times T_{dp})}{\gamma + \Delta};\ °C$$ **[3.10]** (Jensen et al., 1990)

where γ is the *psychometric constant* and is calculated as:

$$\gamma = \frac{c_p \times P}{0.622 \times \lambda};\ kPa \cdot °C^{-1}$$ **[3.11]** (Jensen et al., 1990)

Assuming elevation of sea level, where P=101.3 kPa (barometric pressure) , c_p=1.003 × 10^{-3} MJ kg^{-1} $°C^{-1}$ (specific heat of moist air at constant pressure) and λ=2 453 MJ kg^{-1} (latent heat of vaporization at 20 °C), then

$$\gamma = \frac{1.003 \times 10^{-3} \times 101.3}{0.622 \times 2453} = 0.066\ kPa \cdot C^{-1}$$ **[3.12]** (Jensen et al., 1990)

Slope of the saturation vapor pressure (Δ) is calculated as:

$$\Delta = \frac{4098 \times e}{(T_{dp} + 237.3)^2};\ kPa \cdot °C^{-1}$$ **[3.13]** (Jensen et al., 1990)

Wet bulb depression (WBD)

Wet bulb depression is the difference between the dry bulb and wet bulb temperatures. It indicates the maximum decrease of air temperature by evaporation. This is useful for prediction of decline of temperature due to evaporative cooling. If efficiency of the evaporative cooling system (eff in decimals) is known, the temperature of the cooled air (T_{cool}) can be calculated by the following equation:

$T_{cool} = T_{db} - eff \times (T_{db} - T_{wb})$ **[3.14]** (Bucklin et al., 2004).

A 70% efficient evaporative cooling system at $T_{dp} = 28°C$ and $T_{wb} = 22°C$ can cool the air to $T_{cool} = 28 - 0.7 \times (28 - 22) = 23.8°C$. At the same environmental conditions, but with a 60% and 80% efficient evaporative cooling system, the temperature will be reduced to 24.4°C and 23.2°C, respectively. At saturation, the wet-bulb, dry-bulb, and dew point temperatures are all equal. Otherwise the dew point temperature is less than the wet-bulb, which is less than the dry bulb.

Relative humidity (RH)

Relative humidity is another way of expressing the amount of moisture in the air. RH provides information about saturation of the air at a given temperature. RH can be expressed as a ratio of ambient vapor pressure (e) to saturated vapor pressure (e_s):

$RH = \frac{e}{e_s};\%$ **[3.15]** (Jensen et al., 1990)

When RH is 100 % (dew point), the air is saturated and can absorb no more moisture ($e=e_s$).The amount of water vapor the air can hold increases with temperature. Relative humidity therefore decreases with increasing temperature if the actual amount of vapor (e) stays the same.

Summaries of T_{dp} and T_{wb} for RH between 50 and 100% and Tdb between 20 and 34°C are shown in Table 3.1 and Table 3.2. THI1-THI7 for different relative humidity and temperature are presented in Tables 3. 3–3. 9.

Impact of heat stress on production of cows is alleviated in many dairies by some kind of heat abatement system such as shades, fans, fans and fog misters, fans and sprinklers. Most of these methods rely on evaporative cooling, which delivers droplets of water to the cows' backs and then use airflow to evaporate the water. Evaporative cooling systems with fans and sprinklers deliver water droplets to the cows' backs, and using airflow to evaporate the water, draws heat from the body to the evaporative moisture. Heat abatement systems differ in efficacy of cooling and thus create variation in thermal conditions cows are exposed to.

Thermal relief provided by those devices significantly differs between climatic regions. Climatic conditions in the Southeast United States are characterized by high air temperature associated with high humidity. These hot and humid conditions significantly compromise evaporative heat loss. Because of this phenomenon, evaporative cooling of cows is more successful in dry than humid climates.

The objective of this study was to identify a temperature humidity index most suitable for assessing losses of milk production in U.S. Holstein cows exposed to heat stress in either hot and semi-arid climate of Arizona or hot and humid climate of Georgia.

Data and Methods

Meteorological data used consisted of hourly T_{db} and RH recorded between1993 and 2004 at weather stations in Phoenix, AZ and Athens, GA.

Climatic profile of Phoenix

Climatic conditions in Phoenix can be characterized as dry and with average temperature of 24°C and relative humidity of 32% (Table 3.10.). Figure 3.1 illustrates the annual pattern of diurnal T_{db} and RH cycles in January. Throughout January, T_{db} is ≤ 20 °C the whole day with an average of 13.3°C. In general, temperature and humidity follows a counter-cyclical trend. Therefore at maximum T_{db} minimal RH is usually recorded and vice versa. In January, maximum T_{db} of 19°C is reached between 15:00-17:00, when RH is at its minimum of 30%. Maximum RH of 61 % occurs in the morning hours (5:00- 8:00) simultaneously with minimal temperature of 9 °C. As shown in Figure 3.3, the mean January RH of 47 % is the highest for all months. From March to June mean daily RH declines from 39 to 19%. Mean T_{db} gradually increases from January to July, crossing a borderline of 30°C in May and reaching 35°C in July. As shown in Figure 3.2, with exception of a few hours in the early morning (1:00 – 7:00), temperatures in June are at all hours of the day > 30°C. This suggests that cow's ability to dissipate excessive heat at night can be compromised (Igono, 1962). RH reaches its maximum of 29% in the early morning and then stays below 20% all daytime hours.

Heat stress in Arizona is observed during the months of July and August (Igono, 1992). During May and June, cows are exposed to hot air but because the air is dry (RH is between 22 and 28%) they can be evaporatively cooled and thus less affected by heat stress. The local monsoon season occurring from June to September is associated with a rise of RH. Because of the high RH at these months, the ability to cool cows by evaporative cooling is compromised.

Figure 3.4 presents a monthly pattern of wet bulb depression ($WBD=T_{db}-T_{wb}$). As mentioned earlier, WBD indicates the potential for lowering T_{db} by evaporative cooling. In Phoenix, WBD differs between months. The highest WBD occurs in June, when RH is low and when air has high capacity for evaporation of water. The lowest values are observed from December to March, but evaporative cooling is not employed during these months.

Climatic profile of Athens

The climate in Athens can be described as warm and humid with average temperature of 17°C and RH of 72%. January maximum T_{db} of 11°C occurs between 14:00 and 16:00 when RH is 52 %. Maximum RH of 80% is reached at 6:00 - 8:00 when T_{db} is at its minimum of 3°C.

Larger diurnal changes in RH are observed in June when RH ranges from 93% (at 6:00-9:00 when Tdb is 19°C) to 52% (at 3:00-4:00 when Tdb is 29°C).

Monthly mean temperatures are the lowest in January (6 °C) and peaks in July and August (26 °C). RH stays >70 % for 67% of all days. Summer months (June, July, August September) are characterized by hot weather with high humidity of 75%. In these months, WBD is very low (around 3°C). Because of the high humidity, evaporative cooling doesn't provide any significant relief to the heat stressed cows and decline in milk production is observed (Figure 3.9). In general, efficacy of evaporative cooling systems in Georgia is compromised by high humidity which is present the whole year. In contrast, summer in Phoenix is much warmer but because of the air is dry, it can be cooled by up to 13°C.

Temperature and relative humidity were integrated into seven temperature humidity indices (THI1-THI7) based on equations [3.1-3.13]. Figure 3.5 describes average June diurnal pattern of THI1-THI7. All indices follow a similar trend, with minimum at around 5:00 and maximum between 15:00 and 17:00, however, they differ in height. The largest differences between indices are mainly observed at maximal THI when T_{db} is maximal and RH minimal. Indices with higher weighting of T_{wb} (THI1 and THI2) have much steeper peak than indices with lower weighting (THI5 and THI7). Based on daily (Figure 3.5) and monthly (Figure 3.7) patterns of THI1-THI7 in Phoenix, indices can be classified into three groups: "high" – THI3 and THI4, "medium" – THI2, THI5, THI6 and THI7, 'low" – THI1. On the other hand, investigation of daily (Figure 3.8) patterns of THI1-THI7 in Athens reveals only two groups. The "high" group consists of THI3 and THI4 and the "low" group consists of THI1, THI2 and THI5 through THI7. As shown in Figure 3.8, the "low" group splits into two subgroups (THI1 and THI2 versus THI5, THI6 and THI7) in months of "no heat stress".

Milk yield data

First parity milk yield test-day (TD) records from 58 and 61 herds nearby Athens and Phoenix, respectively, were used. Data from Athens consisted of 110,333 TD records on 12,473 cows with average milk production of 28 kg and DIM of 174 days. Data from Phoenix contained 683,055 TD records on 81,889 cows with average milk production of 30 kg and DIM of 166 days. More detailed statistical description of both data sets is given in Table 3.11.

Seasonal differences in milk yield

Figure 3.9 illustrates seasonal differences in milk production in Athens and Phoenix. Seasonal differences in milk production are caused by periodic changes of environment over the year which has 1) direct effects on the animal - decrease of DMI when ambient temperature is outside of comfort zone and consequently decrease of milk production and 2) indirect effect through fluctuation in quantity and quality of feed. In this study, we will focus only on the first mentioned effect.

March, April and May are months of maximal milk production in Phoenix. Considering THI5 as indicator of heat stress, and assuming heat stress is induced at THI5 $\geq$ 72, decline of milk production should be already detected in May, viz. Figure 3.10. Evaporative coolers are usually set to turn on when $T_{db} \geq 30$ °C, this usually occurs in late April to early May in Phoenix (Igono et al., 1992). Assuming evaporative cooling with efficiency of 60% is employed, THI5 can be reduced to 67, which is below threshold of heat stress. This may explain the absence of decline of milk production in May. However, from June to August, THI climbs from 76 to 81. In these months, even with use of evaporative cooling, THI5 can not drop below 72 (Figure 3.10). This may explain the sharp decline of milk production from June to August. Milk production begins to recover from heat stress in October when THI5 is <72.

In Athens, milk production is at its maximum in April and starts to decline in May However THI5 in May is 67 and therefore no losses of milk production should be expected. This decline could be either explained by effect other than heat stress or it is because THI5 is not a good indicator of heat stress in this humid region. Milk production in June, July and August is significantly compromised by heat stress, in June. Despite that THI5 is much higher in June and July in Phoenix than in Athens, when effect of cooling is considered THI5 declines to the same degree. Recall that WBD and therefore possible decline of temperature with evaporative cooling is low in Athens due to high humidity. In September, environmental conditions in Phoenix are worse than in Athens, even with use of cooling. This is in agreement with Figure 3.9, showing much steeper decline of milk production in Phoenix than in Athens. It indicates that level of heat stress is much higher in Phoenix than in Athens.

Statistical models

Two linear models were employed to compare ability of different THIs to detect losses of milk production due to conditions of excessive temperature and relative humidity.

First, test day milk yield records were analyzed by least square analyses of variance to identify threshold of heat stress, using the PROC GLM procedure in SAS (1999). The model was as follows:

$$y_{ijklm} = hys_i + freq_j + age_k + dim_l + thi_m + e_{ijklm}$$

where hys_i is i^{th} herd x year season class (season defined from December to February, March to May, June to August, September to November), $freq_j$ is j^{th} frequency of milking (j=1,2), age_k is the k^{th} age at calving class (k=1 to 8), dim_l is the l^{th} DIM class (l=1 to 37), thi_m is the m^{th} THI class, and e_{ijklm} is the residual.

Mayer et al. (1999) reported relationship between THI and milk production losses as being either linear, broken-stick or exponential. Igono (1992) found a linear and curvilinear relationship between THI and milk on farms with and without cooling, respectively.

In our study, milk production followed a shape of a broken-stick function (viz. Figures 3.11 – 3.24). It means that milk yield stays constant until a certain point (threshold) and then linearly declines with increasing degree of THI. This was valid for all indices. Least square estimates of milk production per degree of THI were analyzed and threshold of heat stress was identified at the point when decline of milk production exceeded fluctuation of milk production in the thermoneutral period.

The knowledge of the threshold was utilized in the second model, where effect of heat stress was depicted by a linear regression on degrees of heat stress (t), where t was defined as:

$t = 0 \quad if \quad THI \leq threshold \qquad$ *- no heat stress*

$t = THI\text{-}threshold \quad if \quad THI > threshold \qquad$ *- heat stress*

The second fitted model was as follows:

$$y_{ijkl} = hys_i + freq_j + age_k + dim_l + \alpha \times t + e_{ijkl}$$

where α represents a slope of decline of milk production per degree of THI above threshold.

Since indexes are on different scales, comparison can not be done directly by their estimated slope of decline. It was assumed that the index that determines the largest decline in milk yield over its whole scale of the index is the best. Sum of yearly milk yield losses (Δy) identified by a particular index was adopted as a criterion for comparison of indices. The sum of yearly milk yield losses for j^{th} THI and k^{th} region was defined as:

$$\Delta y_{jk} = \alpha_{jk} \sum_{i=1}^{365} t_{ij}$$

where α_{jk} is the rate of decline in milk production identified by j^{th} THI in the k^{th} region and $\sum_{i=1}^{365} t_{ijk}$ is the sum of degrees of heat stress per year for j^{th} THI and k^{th} region.

Results

As shown in Table 3.12, the first model revealed large differences in threshold of heat stress among indices and between regions, ranging from 68 for THI1 in Athens to 83 for THI4 in Phoenix. THI1 and THI2 had the lowest and THI3 and THI4 the highest threshold from all indices in both regions. Thresholds in Athens were on average 3 degrees lower than in Phoenix. This is probably due to more efficient use of cooling devices in Phoenix.

Indices differed in rate of decline (α) of milk production per degree of THI, ranging from -0.40 (THI5) to -0.27 (THI2) in Athens and from -0.59 (THI1) to -0.23 (THI6) in Phoenix. However, because of different scaling (one degree increase in THI doesn't represent the same increase in T_{db} and RH in all indices) and thresholds, direct comparison of indices using α is not possible. Table 3.13 presents losses in milk production per year (Δy) detected by THI1-THI7 in Athens and Phoenix. The largest decline of 127 and 125 kg has been identified by THI2 and THI1, respectively, in Athens. Those indices are characterized by high T_{wb} and T_{db} ratio. In contrast, the lowest decline in Athens (101 kg) has been detected by THI5, by an index with the lowest T_{wb} and T_{db} ratio. On the other hand, THI5 was the best in Phoenix, with Δy of 168 kg. The worst indicator of heat stress was THI1 with Δy of 124 kg. This implies that different indices should be used in humid and different in semi-arid climates. Indices with higher weighting of humidity are more appropriate for humid climates and vice versa.

Disintegrating estimated thresholds of heat stress into T_{db} and RH reveals that heat stress occurs in Athens at temperature ≥ 23°C assuming RH of 75% and in Phoenix at ≥ 30°C and RH of 25%. Assuming that cows in both regions have on average similar heat tolerance, the fact that heat stress occurs in Phoenix at much higher temperature, suggests that more effective strategies are employed to modify the indoor environment of barns in this region.

Conclusions

Temperature humidity indices differ in their ability to detect heat stress. Indices with larger weight on humidity seem to be more suitable for humid climates. On the other hand, in climates when humidity doesn't reach values which could compromise evaporative cooling, indices placing larger weight on ambient temperature than humidity appear to be more appropriate indicators of heat stress. Heat stress occurred in the humid climate of Athens at 3 degrees lower THI than in the semi-arid climate of Phoenix. However, severity of heat stress experienced by a cow over a year was much higher in Phoenix than in Athens. Cautions should be exercised when comparing results from studies using different THI, since various THI represent different environmental conditions and therefore direct comparison is not possible.

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Table 3.1: Dew point temperature (T_{dp} in °C) for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	9	11	12	13	14	15	16	17	18	19	20
22	11	13	14	15	16	17	18	19	20	21	22
24	13	14	16	17	18	19	20	21	22	23	24
26	15	16	18	19	20	21	22	23	24	25	26
28	17	18	20	21	22	23	24	25	26	27	28
30	18	20	21	23	24	25	26	27	28	29	30
32	20	22	23	25	26	27	28	29	30	31	32
34	22	24	25	26	28	29	30	31	32	33	34

Table 3.2: Wet bulb temperature (T_{wb} in °C) for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	14	15	15	16	17	17	18	18	19	19	20
22	16	16	17	18	18	19	20	20	21	21	22
24	17	18	19	19	20	21	21	22	23	23	24
26	19	20	20	21	22	23	23	24	25	25	26
28	21	21	22	23	24	24	25	26	27	27	28
30	22	23	24	25	26	26	27	28	29	29	30
32	24	25	26	27	27	28	29	30	31	31	32
34	26	26	27	28	29	30	31	32	32	33	34

Table 3.3: TH1 for dry bulb temperature (T_{db}) between 20 and and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	59	60	61	62	63	64	64	65	66	67	68
22	62	63	64	65	66	67	68	69	70	71	72
24	65	66	67	68	69	70	71	72	73	74	75
26	68	69	70	71	73	74	75	76	77	78	79
28	71	72	74	75	76	77	78	79	80	81	82
30	74	75	77	78	79	80	82	83	84	85	86
32	77	79	80	81	83	84	85	86	87	88	90
34	80	82	83	85	86	87	88	90	91	92	93

Table 3.4: TH2 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	61	62	63	63	64	65	65	66	67	67	68
22	64	65	66	67	67	68	69	69	70	71	72
24	67	68	69	70	71	71	72	73	74	74	75
26	71	71	72	73	74	75	76	76	77	78	79
28	74	75	76	77	77	78	79	80	81	82	82
30	77	78	79	80	81	82	83	83	84	85	86
32	80	81	82	83	84	85	86	87	88	89	90
34	83	84	85	87	88	89	90	91	91	92	93

Table 3.5: TH3 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	72	72	72	73	73	74	74	75	75	75	76
22	74	75	75	76	76	76	77	77	78	78	79
24	77	77	78	78	79	79	80	80	81	81	82
26	79	80	80	81	82	82	83	83	84	84	84
28	82	83	83	84	84	85	85	86	86	87	87
30	85	85	86	86	87	88	88	89	89	90	90
32	87	88	89	89	90	90	91	91	92	93	93
34	90	91	91	92	93	93	94	94	95	95	96

Table 3.6: TH4 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	73	73	74	74	74	75	75	76	76	76	76
22	75	76	76	77	77	78	78	78	79	79	79
24	78	78	79	79	80	80	81	81	81	82	82
26	81	81	82	82	82	83	83	84	84	84	85
28	83	84	84	85	85	86	86	86	87	87	87
30	86	86	87	87	88	88	89	89	89	90	90
32	88	89	90	90	90	91	91	92	92	92	93
34	91	92	92	93	93	94	94	94	95	95	95

Table 3.7: TH5 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	65	65	65	66	66	66	66	67	67	67	67
22	68	68	69	69	69	70	70	70	71	71	71
24	70	70	71	71	72	72	73	73	74	74	74
26	73	73	74	74	75	76	76	77	77	78	78
28	75	75	76	77	77	78	79	79	80	81	81
30	78	79	79	80	81	82	82	83	84	85	85
32	81	82	83	83	84	85	86	87	88	89	89
34	83	84	85	86	87	88	89	90	91	92	92

Table 3.8: TH6 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	65	66	66	66	67	67	68	68	69	69	69
22	68	68	69	69	70	70	71	71	71	72	72
24	70	71	71	72	72	73	73	74	74	75	75
26	73	74	74	75	75	76	76	77	77	78	78
28	76	76	77	77	78	78	79	79	80	80	81
30	78	79	79	80	81	81	82	82	83	83	84
32	81	81	82	83	83	84	85	85	86	86	87
34	83	84	85	85	86	87	87	88	88	89	90

Table 3.9: TH7 for dry bulb temperature (T_{db}) between 20 and 34 °C and relative humidity between 50 and 100%

T_{db} (°C)	Relative humidity (%)										
	50	**55**	**60**	**65**	**70**	**75**	**80**	**85**	**90**	**95**	**100**
20	65	65	66	66	66	67	67	67	68	68	68
22	67	68	68	69	69	69	70	70	71	71	71
24	70	70	71	71	72	72	73	73	73	74	74
26	73	73	74	74	74	75	75	76	76	76	77
28	75	76	76	77	77	78	78	78	79	79	79
30	78	78	79	79	80	80	81	81	81	82	82
32	80	81	82	82	82	83	83	84	84	84	85
34	83	84	84	85	85	86	86	86	87	87	87

Table 3.10: Descriptive statistics of weather data from Athens and Phoenix

	Athens				Phoenix			
Daily minimum	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
RH (%)	50	17	16	96	19	8	5	48
T_{db} (°C)	12	7	-4	23	18	8	3	33
T_{wb} (°C)	11	7	-6	23	12	6	1	23
T_{dp} (°C)	9	9	-12	22	1	7	-14	18
THI1	52	13	22	73	55	11	33	76
THI2	52	13	23	74	57	12	34	79
THI3	63	11	40	80	68	10	50	87
THI4	65	10	42	81	69	10	50	88
THI5	54	12	28	74	61	10	39	80
THI6	57	11	33	74	62	10	43	80
THI7	57	10	34	73	61	10	42	80
Daily average	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
RH (%)	72	13	39	99	32	13	11	74
T_{db} (°C)	17	7	1	29	24	8	9	38
T_{wb} (°C)	14	7	-1	24	15	5	4	24
T_{dp} (°C)	11	8	-8	23	4	7	-9	20
THI1	58	12	31	76	61	10	42	79
THI2	59	12	31	78	64	11	43	83
THI3	69	10	47	85	75	10	56	91
THI4	70	10	48	86	74	10	56	92
THI5	61	11	36	79	67	9	50	83
THI6	63	10	40	78	68	9	50	85
THI7	62	10	40	78	66	10	48	84
Daily maximum	**Mean**	**SD**	**Min**	**Max**	**Mean**	**SD**	**Min**	**Max**
RH (%)	93	8	60	100	50	18	19	100
T_{db} (°C)	23	7	6	36	30	8	13	45
T_{wb} (°C)	17	6	3	27	18	5	8	27
T_{dp} (°C)	14	7	-6	26	8	6	-6	23
THI1	64	11	38	81	68	10	47	86
THI2	66	11	39	85	72	11	49	92
THI3	76	9	53	91	82	9	62	99
THI4	77	9	54	93	81	10	61	98
THI5	69	10	45	85	73	8	57	88
THI6	69	9	47	85	75	9	56	93
THI7	69	10	45	85	73	10	53	90

Table 3.11: Descriptive statistics of performance data (1993-2004) from herds nearby Athens and Phoenix

	Athens				Phoenix			
	Mean	SD	Min	Max	Mean	SD	Min	Max
Number of records	110,480	-	-	-	683,876	-	-	-
Number of cows	12,473	-	-	-	81,889	-	-	-
Number of herds	61	-	-	-	53	-	-	-
Number of test days per cow	9	2	1	13	8	2	1	17
Days in milk	174	97	5	365	166	93	5	365
Milk (kg)	28	7	2	59	30	7	2	79
Distance between herd and weather station (km)	32	9	2	51	23	14	10	70

Table 3.12: Threshold of heat stress and rate of decline (α) of milk production (in kg) due to heat stress for seven THIs

	Athens		Phoenix	
	Threshold	α (kg)	Threshold	α (kg)
THI1	68	-0.29	73	-0.59
THI2	69	-0.27	74	-0.26
THI3	78	-0.38	83	-0.29
THI4	79	-0.37	82	-0.28
THI5	72	-0.40	74	-0.31
THI6	72	-0.39	75	-0.23
THI7	71	-0.37	74	-0.28

Table 3.13: Ratio of T_{wb} and T_{db} (T_{wb} :T_{db}) in THI1-THI7, yearly heat stress degrees and yearly losses (Δy) in milk production due to heat stress detected by THI1-THI7 in Athens and Phoenix, rank of THI based on Δy

		Athens			Phoenix		
	T_{wb}:T_{db}	Heat street degrees	Δy (kg)	Rank	Heat street degrees	Δy (kg)	Rank
THI1	5.7	436	-125	2	211	-124	7
THI2	1.9	471	-127	1	536	-142	5
THI3	1.0	302	-113	3	447	-131	6
THI4	1.2	291	-109	4	580	-163	2
THI5	0.3	255	-101	7	542	-168	1
THI6	1.0	264	-104	6	634	-147	4
THI7	1.2	285	-105	5	585	-162	3

Figure 3.1: Average diurnal pattern of January dry bulb temperature (T_{db} in °C) and relative humidity (RH in %) in Phoenix and Athens

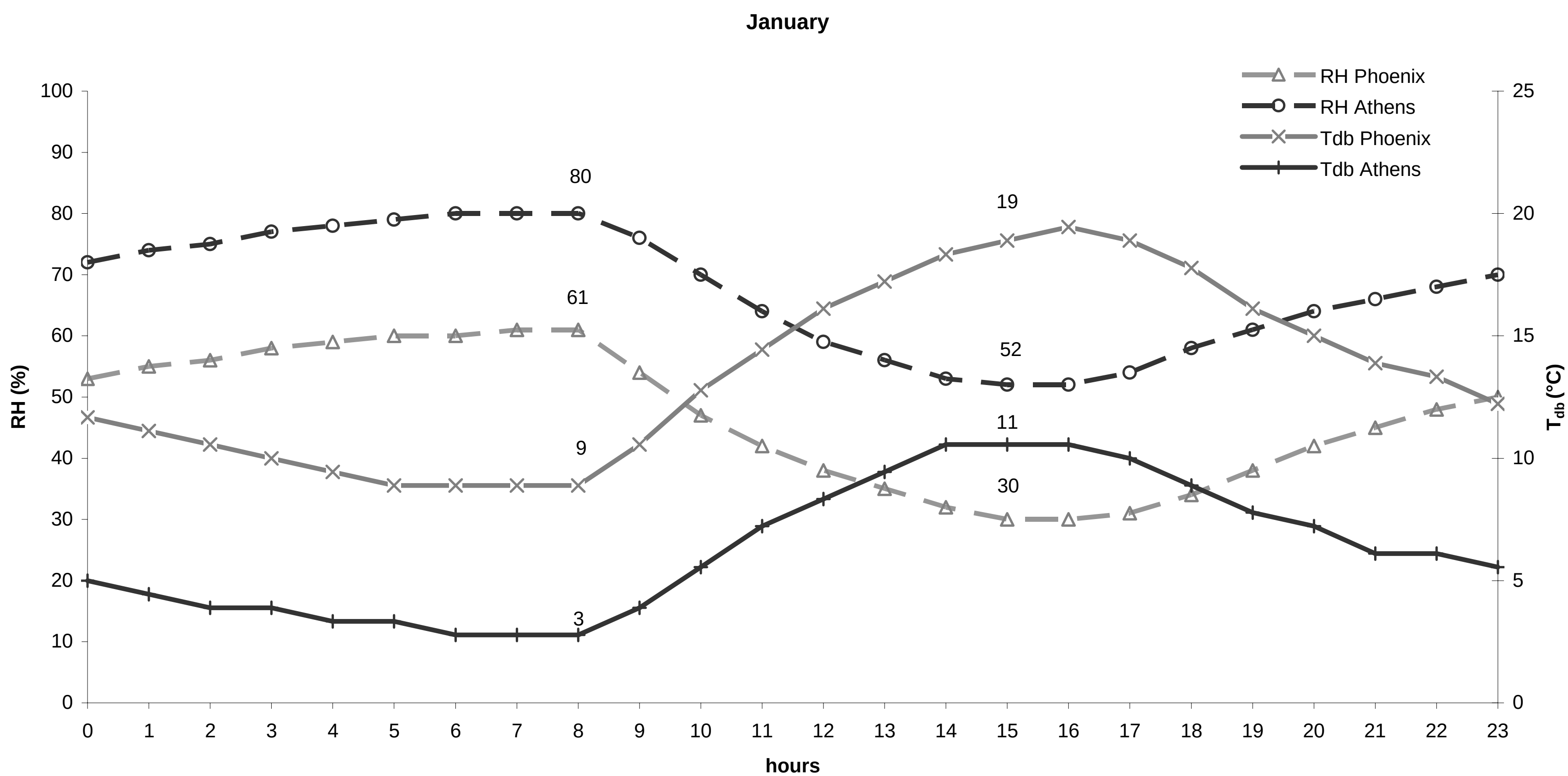


Figure 3.2: Average diurnal pattern of June dry bulb temperature (T_{db} in °C) and relative humidity (RH in %) in Phoenix and Athens

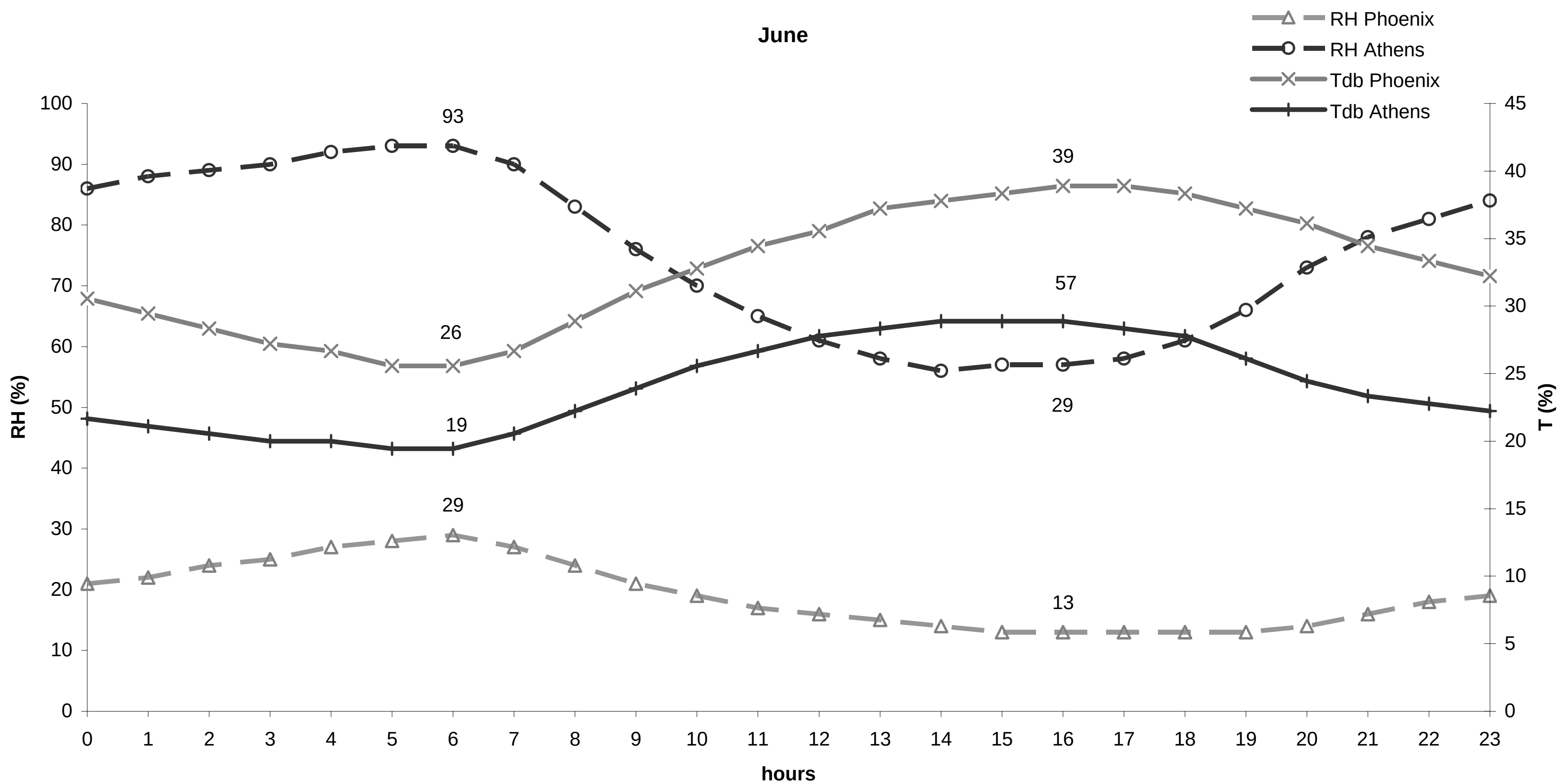


Figure 3.3: Average monthly pattern of dry bulb temperature (T_{db} in °C) and relative humidity (RH %) in Athens and Phoenix

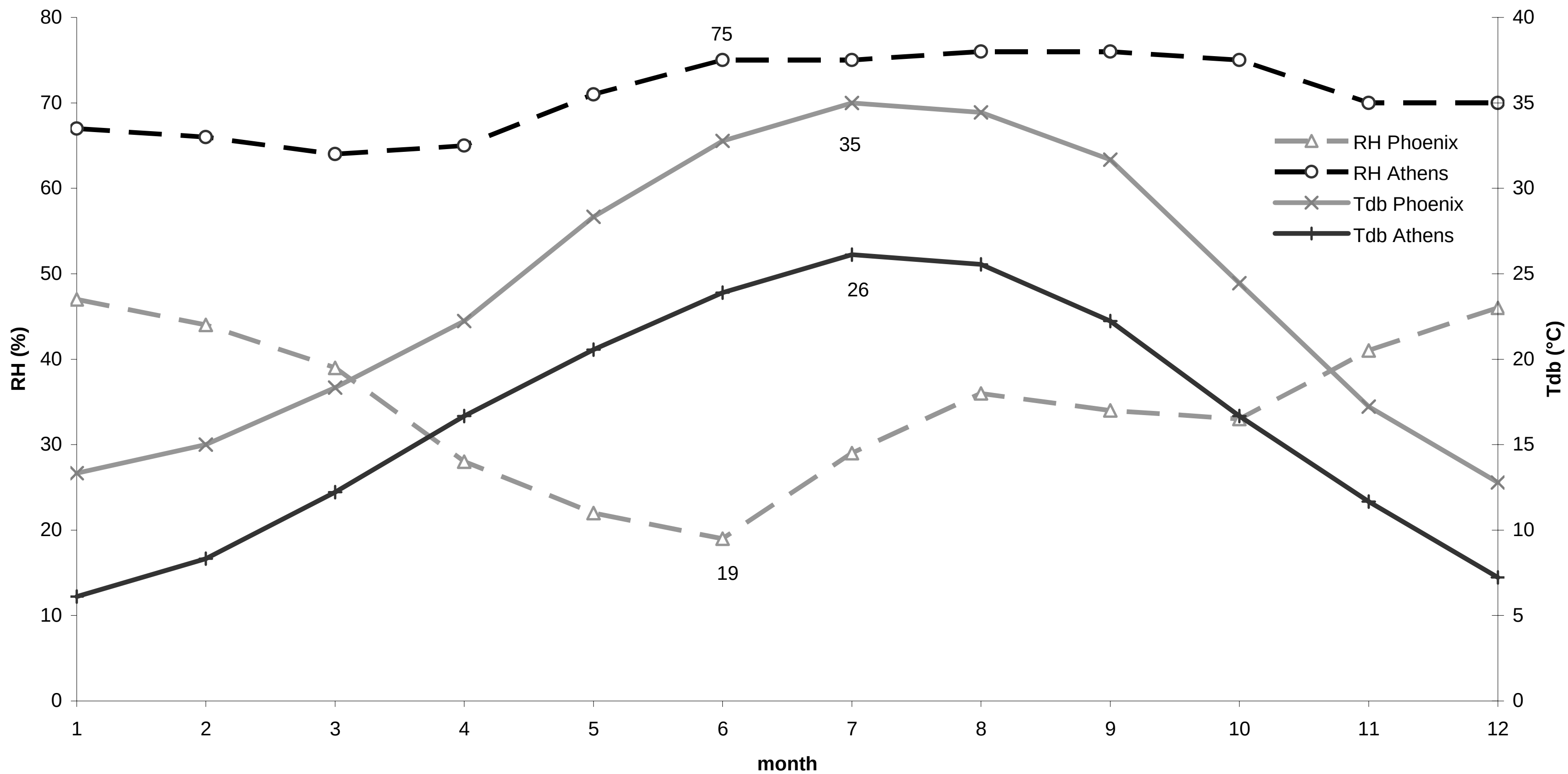


Figure 3.4 Average monthly pattern of wet bulb depression (WBD in °C) in Phoenix and Athens

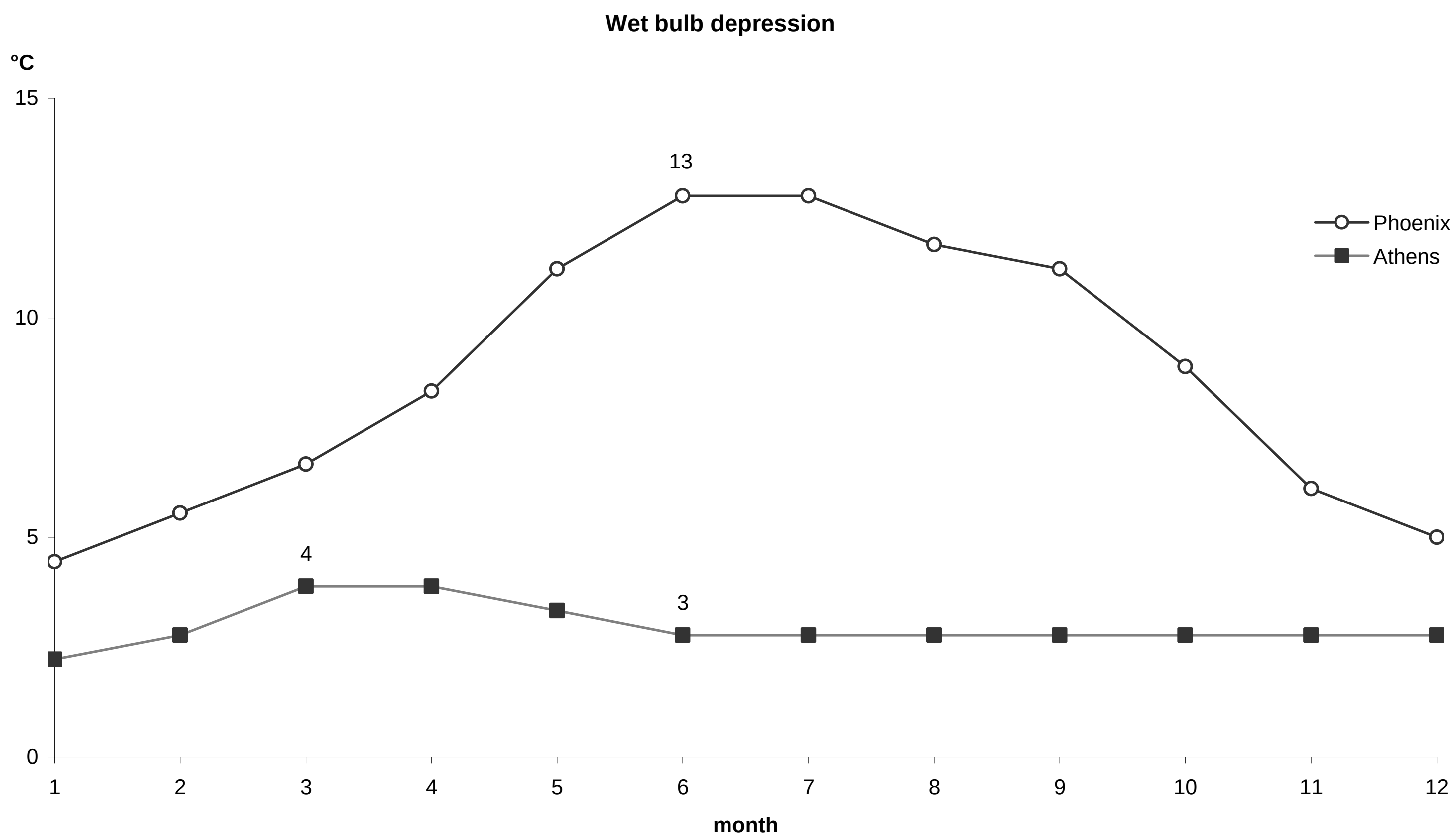


Figure 3.5: Average June diurnal pattern of temperature humidity indices (THI 1- THI 7) in Phoenix

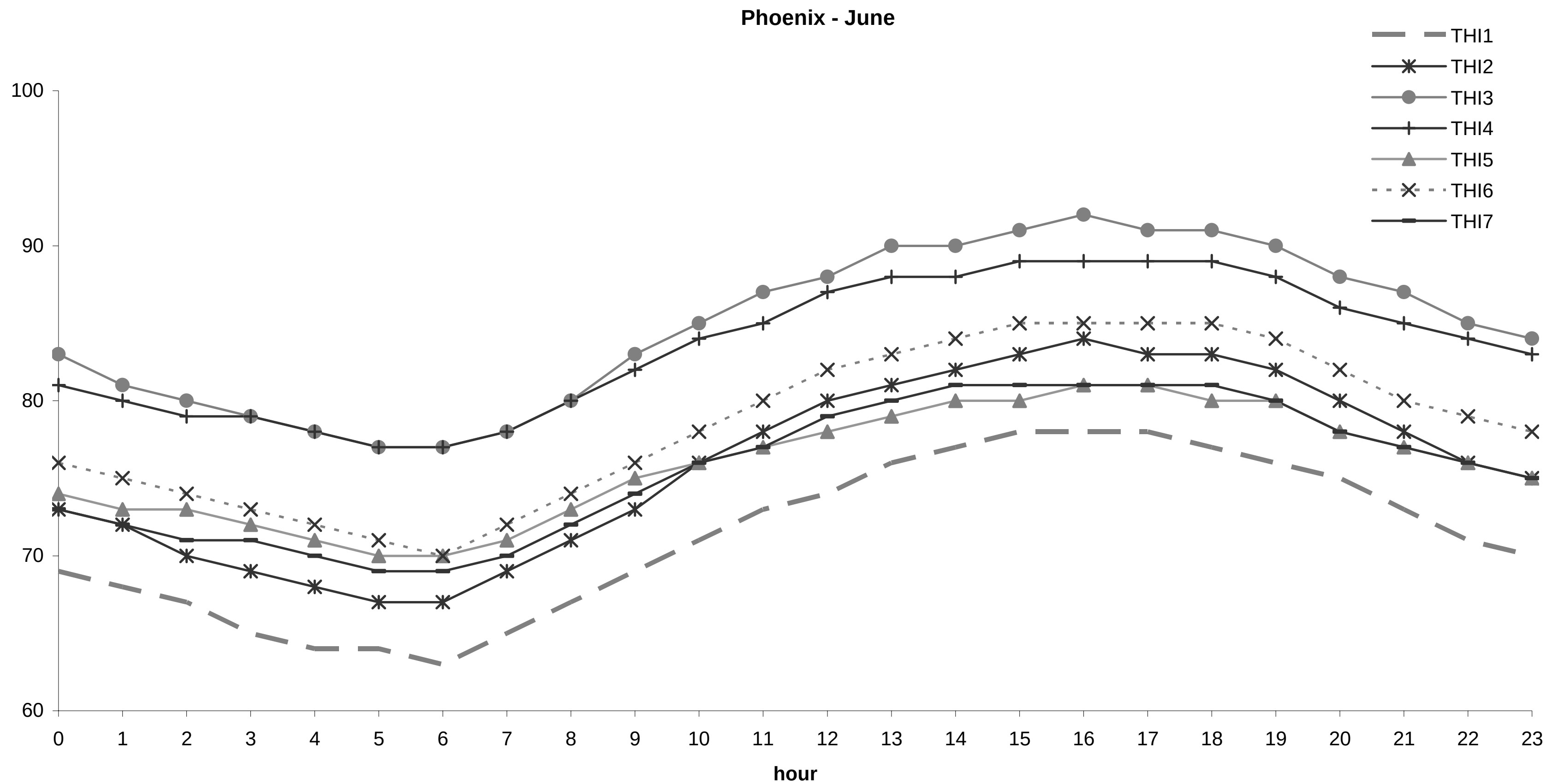


Figure 3.6: Average June diurnal pattern of seven temperature humidity indices (THI1-THI7) in Athens

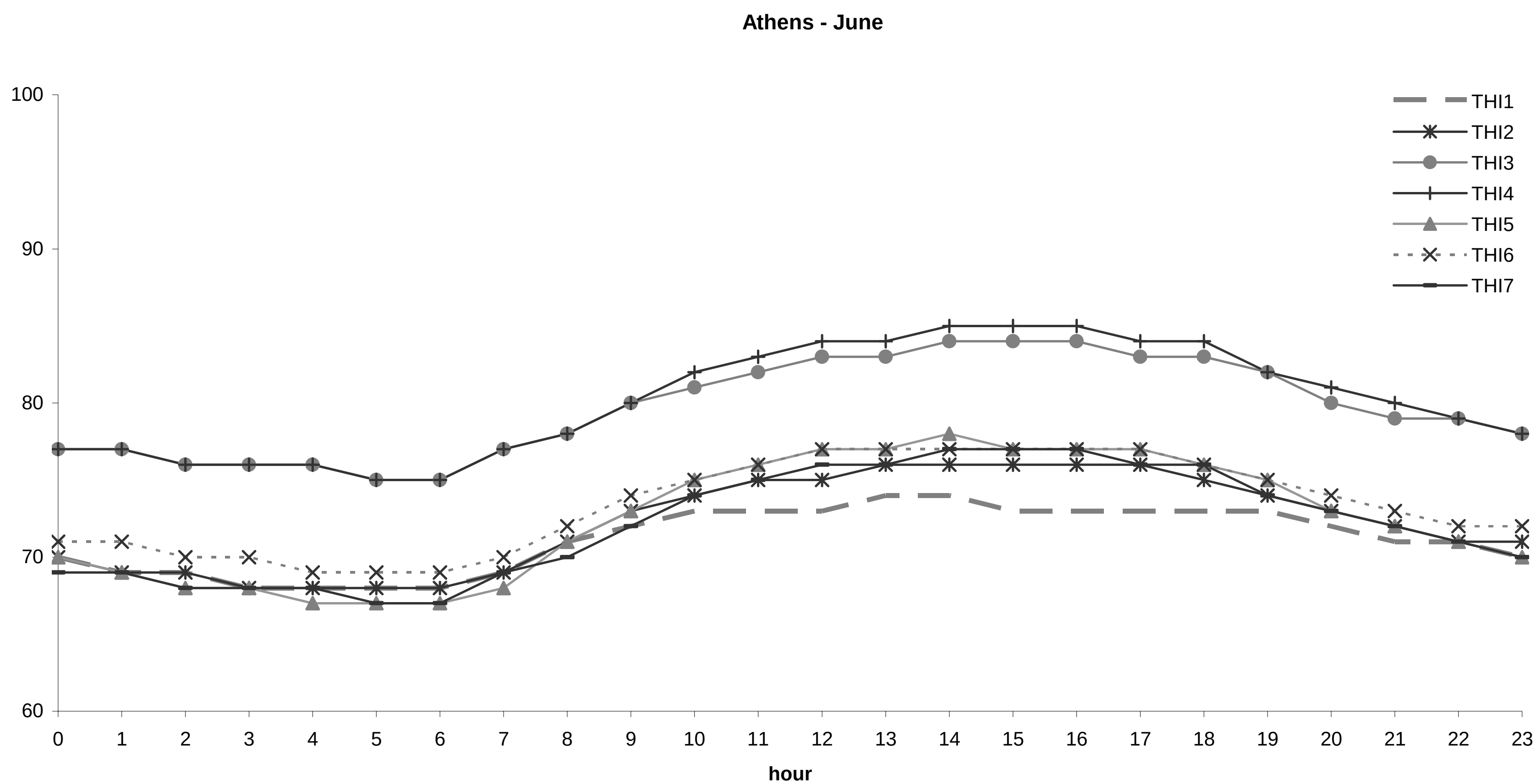


Figure 3.7: Average monthly pattern of THI1- THI7 in Phoenix

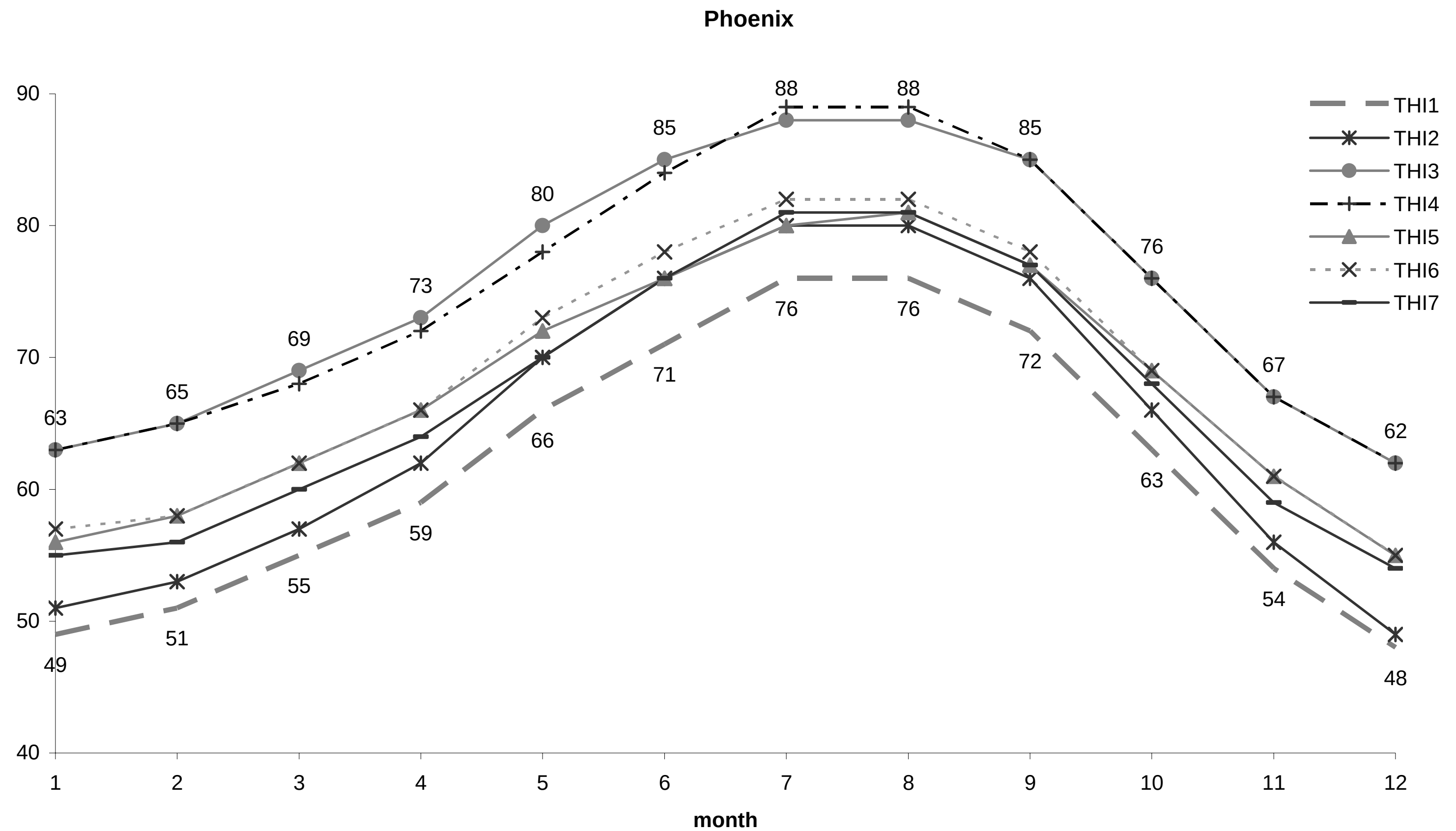


Figure 3.8: Average monthly pattern of THI1- THI7 in Athens

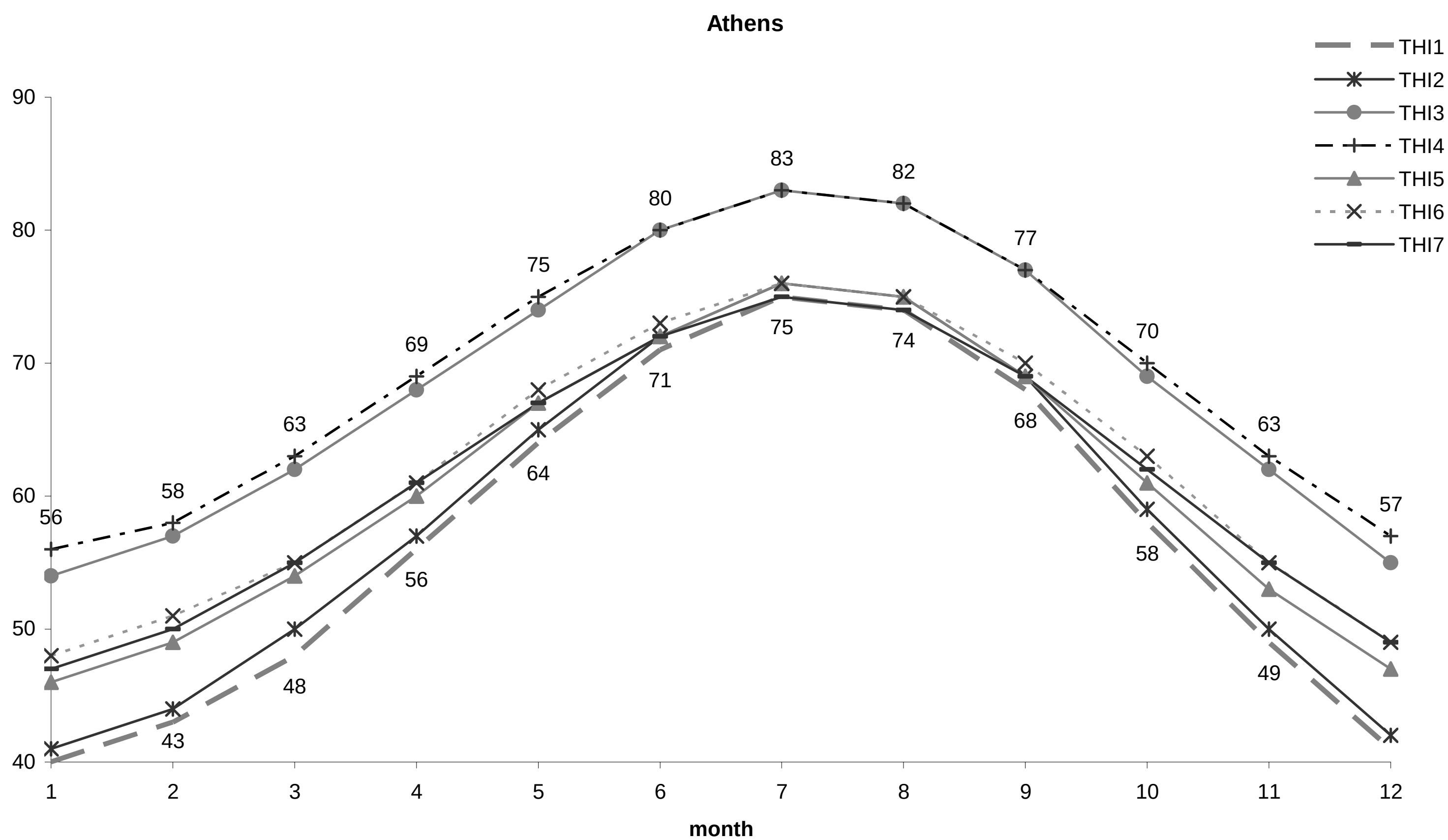


Figure 3.9: Seasonal differences in milk production in herds near Athens and Phoenix

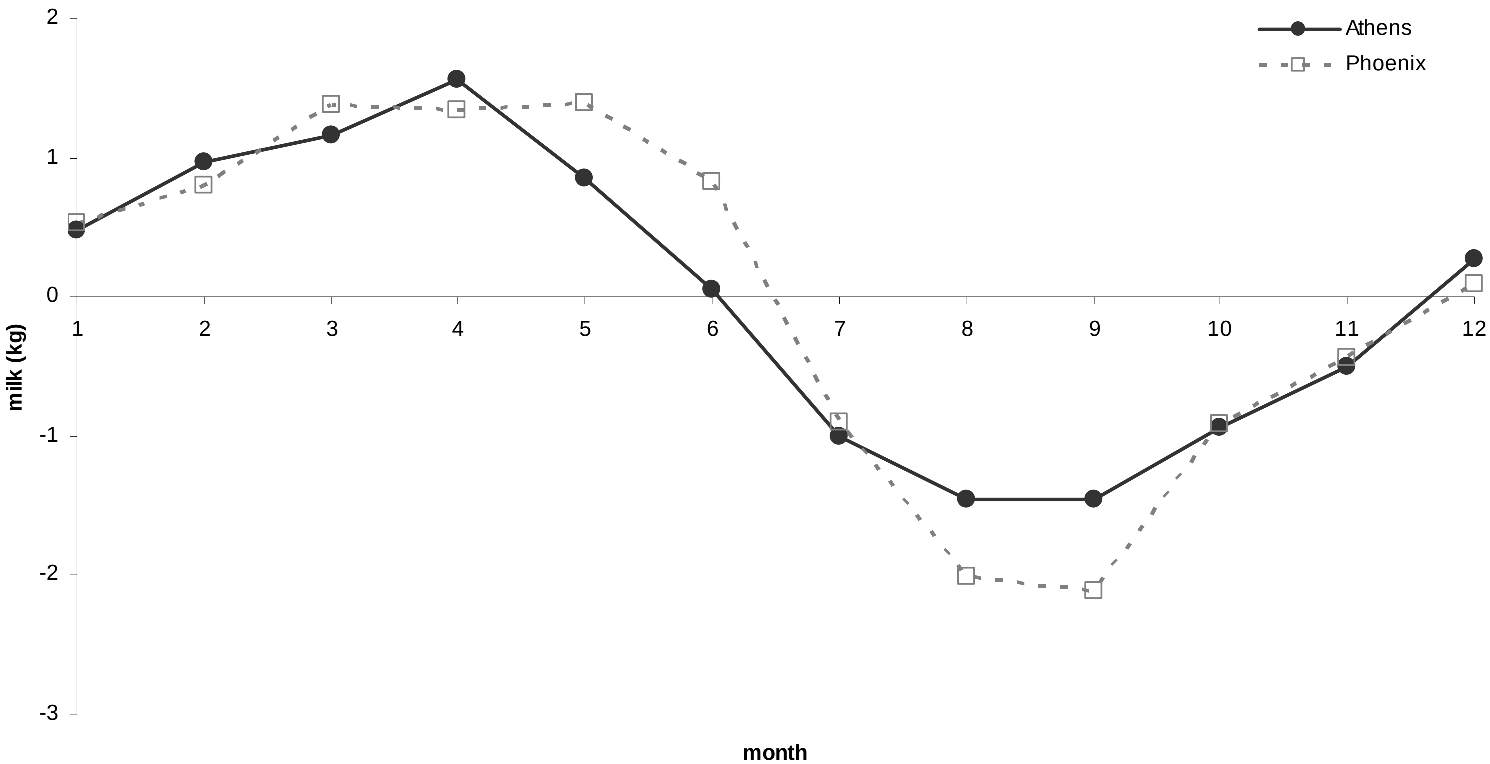


Figure 3.10: Temperature humidity index (THI5) with (cooled) and without (not cooled) accounting for use of evaporative cooling

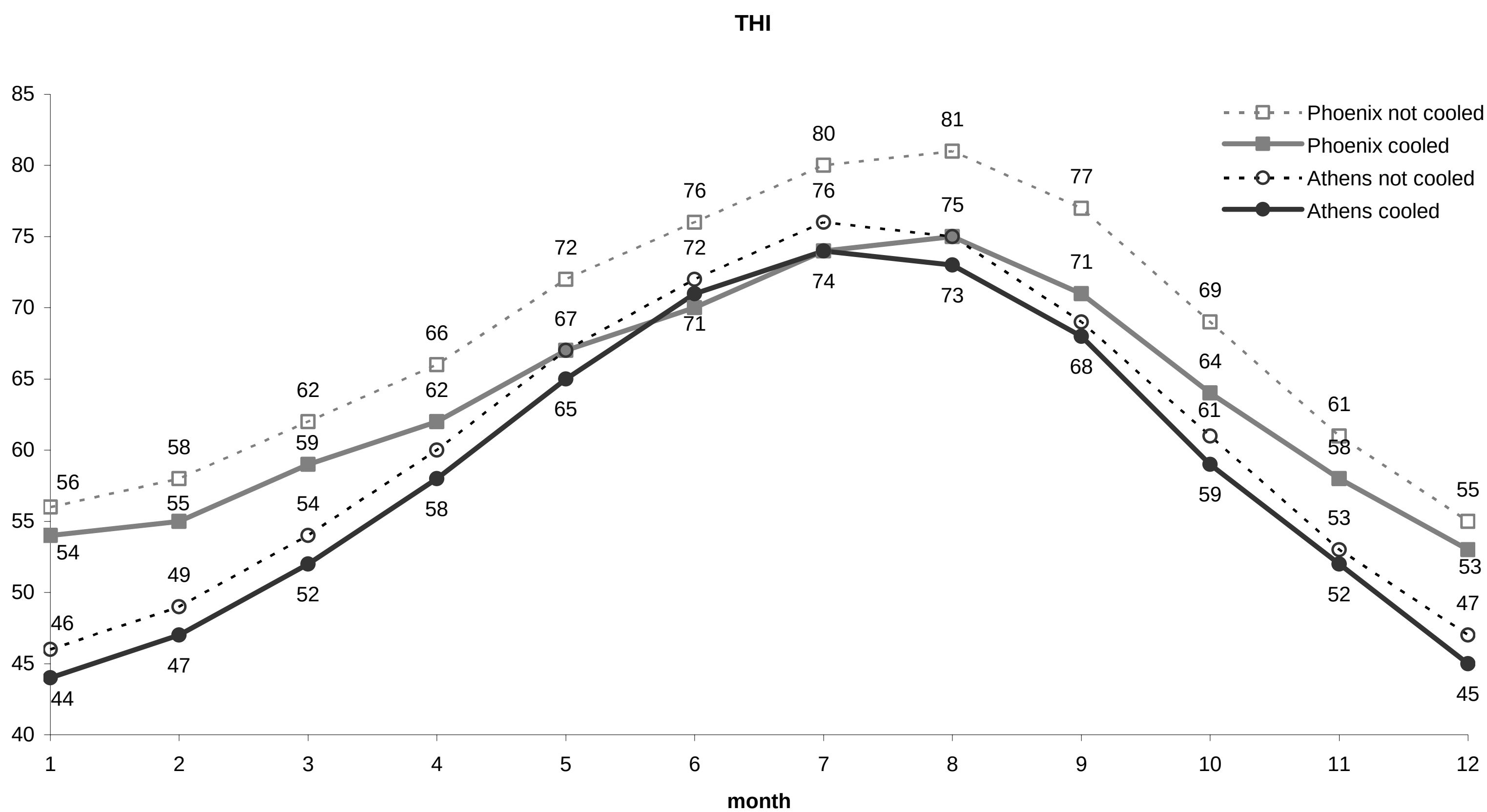


Figure 3.11: Least square estimates (x), regression on degrees of THI1 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

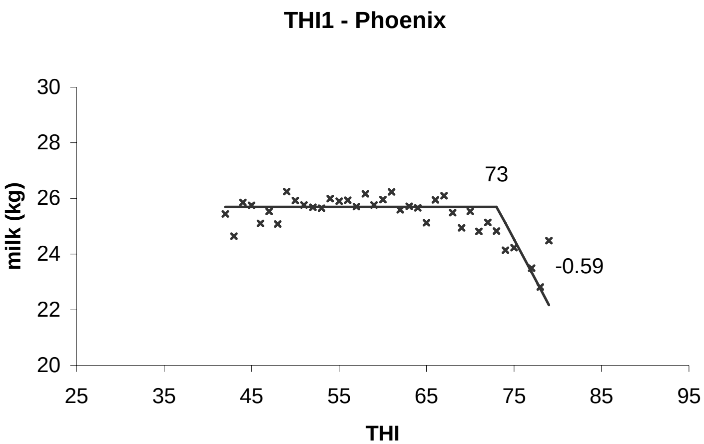


Figure 3.12: Least square estimates (x), regression on degrees of THI1 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

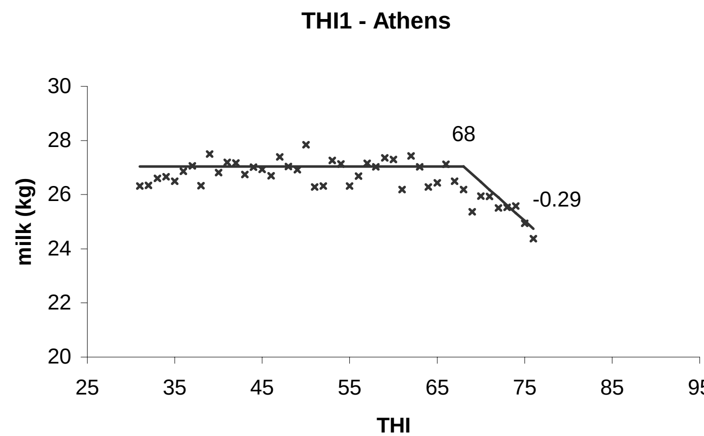


Figure 3.13: Least square estimates (x), regression on degrees of THI2 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

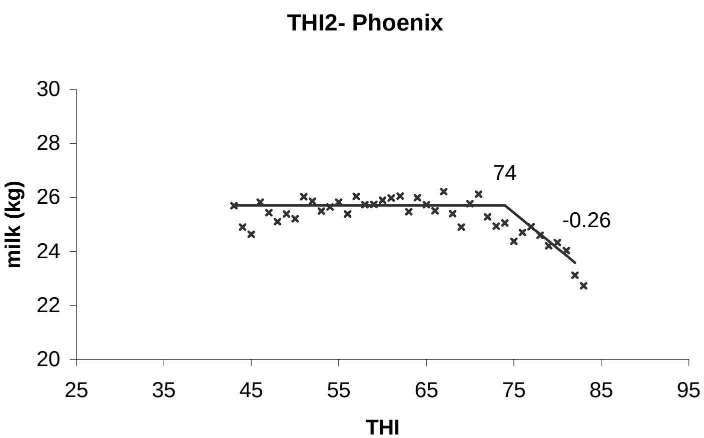


Figure 3.14: Least square estimates (x), regression on degrees of THI2 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

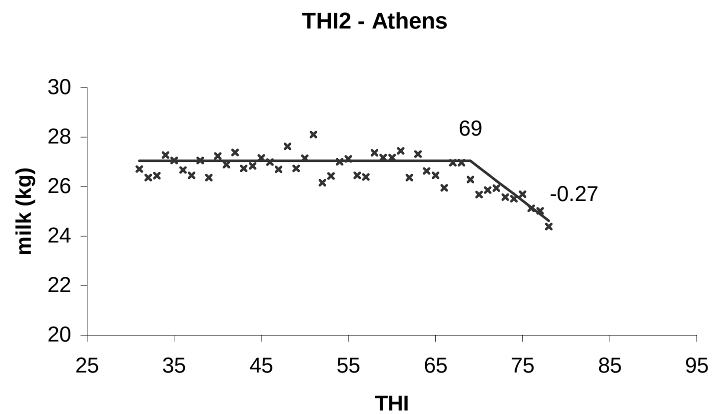


Figure 3.15: Least square estimates (x), regression on degrees of THI3 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

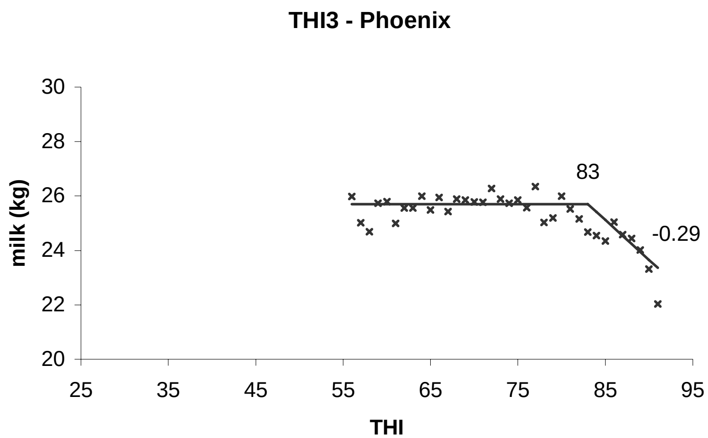


Figure 3.16: Least square estimates (x), regression on degrees of THI3 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

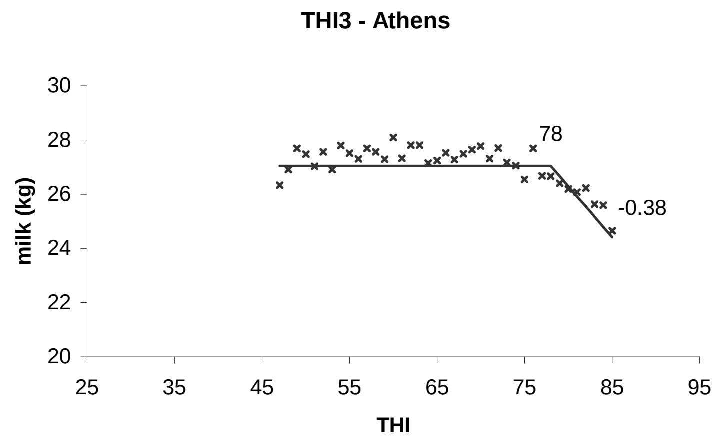


Figure 3.17: Least square estimates (x), regression on degrees of THI4 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

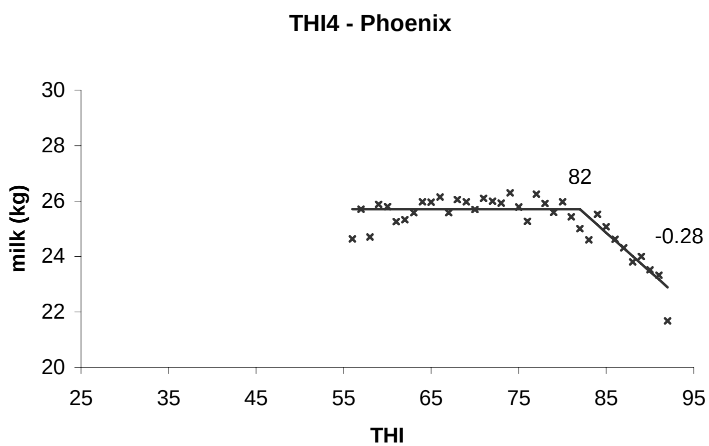


Figure 3.18: Least square estimates (x), regression on degrees of THI4 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

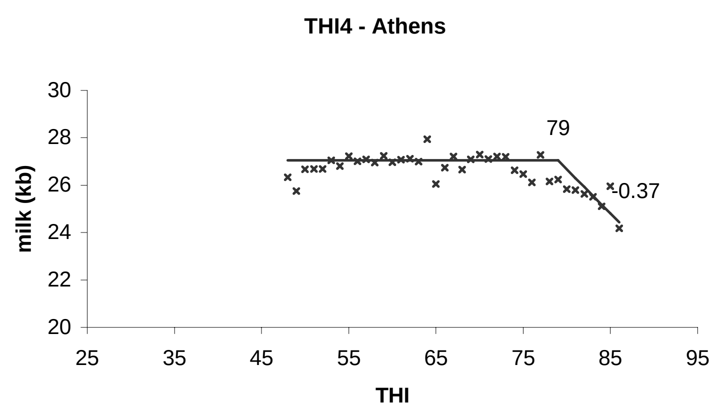


Figure 3.19: Least square estimates (x), regression on degrees of THI5 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

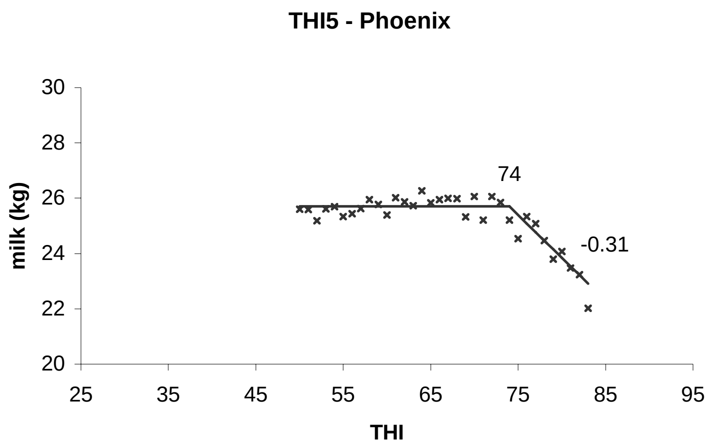


Figure 3.20: Least square estimates (x), regression on degrees of THI5 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

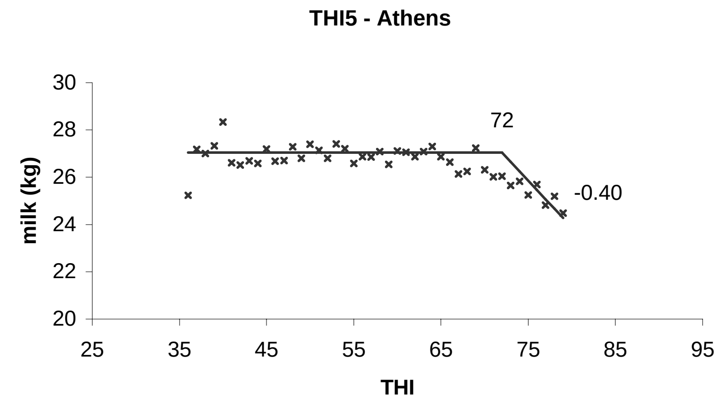


Figure 3.21: Least square estimates (x), regression on degrees of THI6 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

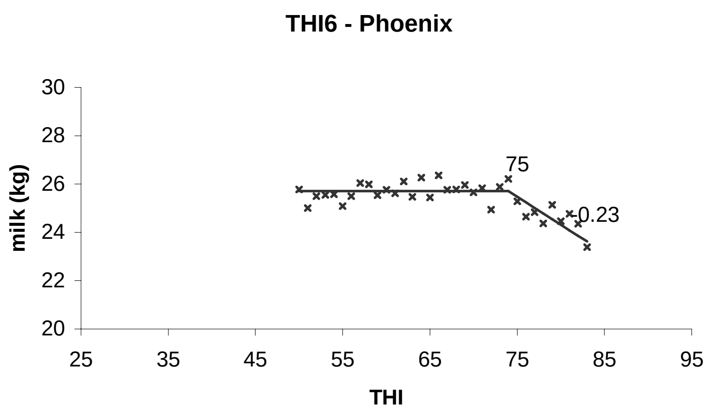


Figure 3.22: Least square estimates (x), regression on degrees of THI6 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens

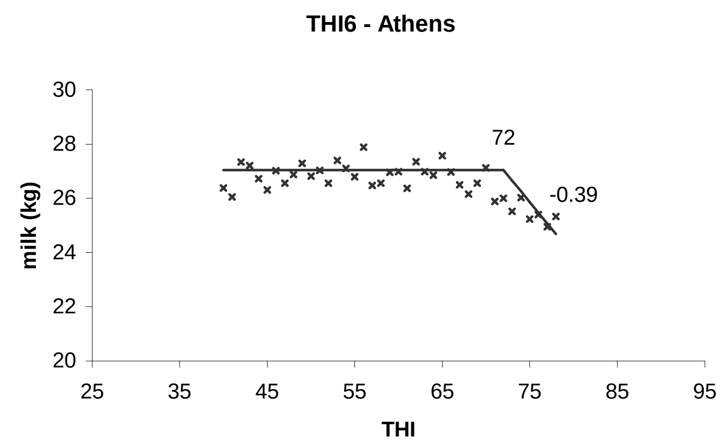


Figure 3.23: Least square estimates (x), regression on degrees of THI7 (solid line), a threshold of heat stress and a slope of decline of milk yield in Phoenix

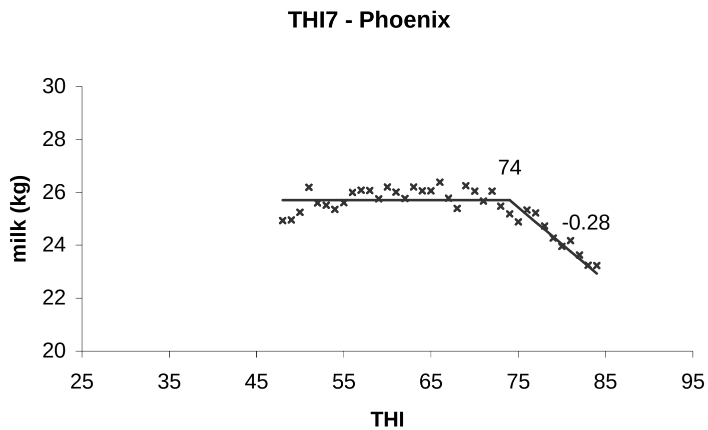
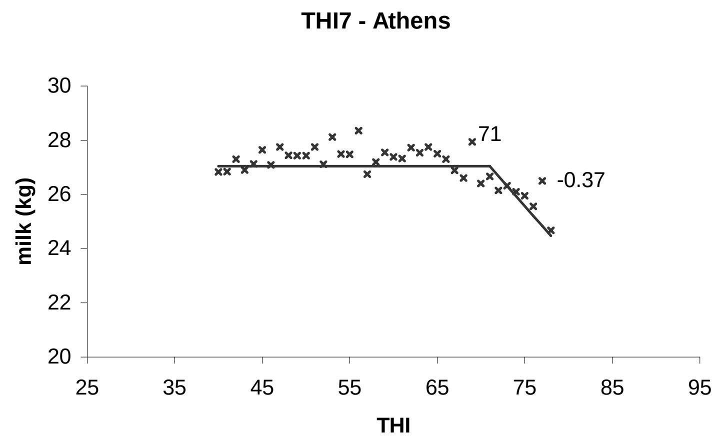


Figure 3.24: Least square estimates (x), regression on degrees of THI7 (solid line), a threshold of heat stress and a slope of decline of milk yield in Athens



CHAPTER 4

NATIONAL GENETIC EVALUATION OF MILK YIELD FOR HEAT TOLERANCE OF UNITED STATES HOLSTEINS

J. Bohmanova, I. Misztal, S. Tsuruta, H.D. Norman, T. J. Lawlor. 2005. *Interbull Bulletin*. 33:160-162. (modified)

Abstract

The objective of this study was to conduct a national genetic evaluation of milk yield for heat stress and to identify genetically heat tolerant Holstein bulls. Production data consisted of 57 million test-day records of 7 million primiparous Holstein cows that calved from 1993 through 2004. Hourly temperature and relative humidity records were available from 202 public weather stations across the United States. The repeatability test-day model included fixed effects of herd-test date, days in milk class, frequency of milking, age at calving,   Based on estimated heat tolerance PTAs, the 100 most and 100 least heat-tolerant sires were selected. For each of the 200 sires, official U.S. PTAs from February 2006 were obtained. Sires that were the most heat tolerant transmitted lower milk yields with higher fat and protein contents than did sires that were the least heat tolerant. Daughters of the most heat tolerant sires had better udder and body composites, better type, lower dairy form, slightly higher TPI, longer productive life, higher daughter pregnancy rate, easier calving and better persistency than did daughters of the least heat tolerant sires. Continued selection for milk yield without consideration of heat tolerance may result in greater susceptibility to heat stress.

Introduction

Heat stress is an important factor that significantly affects production and reproduction of dairy cattle in the United States. Estimated total annual economic losses to the dairy industry due to heat stress range from $897 to $1500 million (St-Pierre et al., 2003). Therefore, genetic selection for improved heat tolerance could be a cost effective solution of this problem.

Selection on production in an optimal environment results in increased sensitivity in a harsh environment (van der Waaij, 2004). The long-term selection of U.S. Holstein cattle for milk production was carried out mainly in a temperate climate, and could have lead to an increase of sensitivity to heat stress over the years.

The level of heat stress can be measured by an animal's response to climatic conditions. Climatic conditions can be described by a combination of environmental factors such as air temperature, solar radiation, relative humidity, and wind speed. However, the majority of these variables is not recorded in a consistent way and therefore can not be used for a national evaluation. The temperature humidity index (THI) combines dry bulb temperature and relative humidity and is a popular choice for large scale studies because both variables are recorded daily at public weather stations. Meteorological data from weather stations provide an accurate description of environmental conditions for farms even miles away. However, if cooling devices are used on the farm, the actual climatic conditions in the barn are different from those at the weather station. This fact can obscure identification of the real effect of heat stress. Unfortunately, accounting for the effect of cooling is compromised by a lack of adequate records on use and efficiency of these heat abatement devices.

More efficient metabolism and consequently lower heat production is one of the main characteristics of a heat tolerant animal (Lee, 1953). In a harsh environment more resources are required for fitness and health related traits than in an optimal environment. A heat tolerant cow which metabolizes nutrients more effectively has more resources for fitness, health, and reproduction, compared to her heat sensitive contemporaries. On this basis, it can be hypothesized that a heat tolerant cow is more resistant not only to heat stress but also to other stressors such as diseases, feed quality and quantity and parasites. In such a heat tolerant cow, improved fertility and fewer health problems can lead to a longer productive life.

Ravagnolo and Misztal (2000) presented a methodology for genetic evaluation of heat tolerance using test-day milk yield and climatic records from weather stations. The authors separated predicted transmitting ability into a part describing genetic potential for milk production in thermoneutral environments (traditional PTA) and a part describing genetic potential for milk production under thermal conditions (PTA for heat tolerance). When this approach was applied to the test-day milk yield of Holstein cows in Georgia, a genetic correlation of -0.35 was found between the traditional and heat tolerance PTAs, and the genetic variance of heat tolerance PTAs was large at high THI. This indicates a need for a separate selection in temperate and thermal climates and suggests a potential for genetic selection of milk yield under these conditions.

The objective of this study was to run a genetic evaluation of milk yield for heat stress at the national level and to identify genetically heat tolerant Holstein bulls.

Materials and Methods

Data

The U.S. national data set consisted of 57,315,661 first-parity test-day records of 6,906,815 Holsteins that calved from 1993 through 2004. Hourly temperature and relative humidity records were available from 202 public weather stations across the United States. Herds were assigned by distance to the nearest weather station.

Hourly THIs were computed from hourly dry bulb temperature (T_{db}) expressed in °C and relative humidity (RH) expressed as a percentage (National Research Council, 1971):

$$THI = (1.8 \times T_{db} + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26)]$$

Hourly THIs were used to calculate average daily THI (avgTHI). A dummy regression variable t was defined to estimate decline of milk production due to heat stress. The threshold for heat stress was assumed at avgTHI 72. Therefore

if avgTHI< 72 *then* t=0 (no heat stress)

else if avgTHI ≥ 72 *then* t=avgTHI-72

Model

The random regression repeatability model used for genetic evaluation of test day milk yields (y) was

$$y_{ijklmn} = htd_i + \dim_j + age_k + freq_l + a_m + p_m + \alpha_m t + \pi_m t + e_{ijklmn}$$

where htd_i is the fixed effect of the i^{th} herd-test date (i=1 to 2,658,042), dim_j is the j^{th} DIM class (j=1 to 37), with classes defined every 10 days, age_k is the k^{th} age at calving class (k=1 to 8), $freq_l$ is l^{th} frequency of milking (l= 1 to 2), a_m is the traditional additive genetic effect for animal m (m=1 to 10,673,333), p_m is the permanent environmental effect for animal m, α_m is the additive genetic random regression effect of heat tolerance for animal m, π_m is the permanent environmental random regression effect of heat tolerance for animal m, and e_{ijklmn} is residual.

The variance-covariance structure was:

$$\mathrm{var}\begin{bmatrix} a \\ \alpha \\ p \\ \pi \\ e \end{bmatrix} = \begin{bmatrix} A\sigma_a^2 & A\sigma_{a\alpha} & 0 & 0 & 0 \\ A\sigma_{a\alpha} & A\sigma_\alpha^2 & 0 & 0 & 0 \\ 0 & 0 & I\sigma_p^2 & I\sigma_{p\pi} & 0 \\ 0 & 0 & I\sigma_{p\pi} & I\sigma_\pi^2 & 0 \\ 0 & 0 & 0 & 0 & I\sigma_e^e \end{bmatrix}$$

where **A** is the relationship matrix, **I** is the identity matrix, σ^2 denotes variance, and σ covariance. Genetic and environmental parameters were those estimated by Ravagnolo and Misztal (2000).

Results

The PTAs of 172,411 sires and 10.5 million cows were calculated by BLUP90IOD (Tsuruta, 2001) in 144 rounds and 8 hours. Heat tolerance PTAs of sires ranged from -0.48 to 0.38 kg milk per THI unit > 72 per day; traditional milk yield PTAs for sires were between -8.9 and 7.9 kg per day.

Based on estimated heat tolerance PTAs, the 100 most and 100 least heat tolerant sires were selected. For each of the 200 sires, official U.S. PTAs for February 2006 were obtained (Table 4.1). Sires that were the most heat tolerant transmitted lower milk yields with higher fat and protein contents than did sires that were the least heat tolerant. Daughters of the most heat tolerant sires had better udder and body composites, better type, lower dairy form, slightly higher TPI, longer productive life, higher daughter pregnancy rate and calved easier than did daughters of the least heat tolerant sires. Daughters of heat tolerant bulls were more persistent in milk, fat and protein.

Average state PTAs for milk and heat tolerance were calculated as a weighted average (weighted by number of daughters) of PTAs of bulls having daughters in that state. As given in Table 4.2, the states in the Southeast and Southwest of the United States were ranked high for milk but were below average for heat tolerance. Producers in these states are paid based on a fluid milk pricing system (Bailey and Tozer, 2001). This pricing scheme provides incentives to select for cows with high milk yield without consideration for solid component content (fat and protein content). As shown in this study, sires with higher PTAs for milk yield transmit lower heat tolerance to their daughters. It is possible that due to the use of the less heat tolerant sires, the problem of heat stress in these regions may have been even compounded.

As presented in Figure 4.1, heat tolerance has slightly declined over the years. An improvement of heat tolerance can be observed after 1995. However, the changes are diminutive. Similar trend can be seen in daughter pregnancy rate, which declined from 1980 to 1994 and then increased from 1995 to 1998. The abrupt change in the trend in 1995 can be either attributed to a smaller number of daughters of sires born after 1995 and consequently lower accuracy of their proofs, or it could be due to the change in selection strategy. Nonyield traits (productive life and somatic cell score) were added to the selection index in 1994 (Shook, 2006).

Figure 4.2 shows a trend of 305 day PTAs and test-day PTAs in temperate and heat stress conditions. The latter PTA was calculated as a sum of heat stress PTA multiplied by the average number of heat stress degrees per day plus the traditional PTA. The average number of heat stress degrees per day was set to 1.5, which corresponds to climatic conditions in the southern United States. The PTA in temperate conditions is simply the traditional PTA. The PTA for 305 day milk yield increased linearly from 1980 to 1998. Predicted transmitted abilities for milk production in the thermal and heat stress environment were almost identical. Both test-day PTAs showed a negative trend after 1995. This could have resulted from assumptions imposed by the model used in this study. The model does not account for differences in persistency, and thus it could have underestimated younger animals with flatter lactations curves and consequently created an erroneous negative trend. It will require further investigation to confirm this hypothesis.

Conclusions

Bulls that transmitted high tolerance to heat stress had daughters with lower milk yields, higher content of milk solids, better udders, longer productive lives, easier calvings, higher pregnancy rates and better persistency. Continued selection for milk yield without consideration of heat tolerance may result in greater susceptibility to heat stress.

Acknowledgements

Weather data were available through the Southern Regional Climate Center (Baton Rouge, LA) as a cooperative effort between Louisiana State University, the National Climatic Data Center, and the National Weather Service and were provided by J.B. Cole, Animal Improvement Programs Laboratory, USDA (Beltsville, MD).

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Table 4.1: Average PTAs and TPIs from February 2006 U.S. official evaluation for the 100 most and 100 least heat tolerant U.S. Holstein bulls

	100 most heat tolerant bulls	100 least heat tolerant bulls	Difference between most and least heat tolerant bulls
Milk (kg)[1]	-732.47	378.85	-1111.32
Fat (kg)[1]	-6.31	7.13	-13.44
Protein (kg)[1]	-14.44	4.25	-18.69
Fat (%)[1]	0.08	-0.02	0.11
Protein (%)[1]	0.03	-0.03	0.06
Udder composite[2]	0.15	-0.58	0.73
Body composite[2]	0.64	0.03	0.61
Dairy composite[2]	0.94	0.70	0.24
Type[2]	0.08	-0.46	0.54
Stature[2]	0.02	-0.31	0.32
Strength[2]	0.20	-0.24	0.43
Body depth[2]	0.08	0.02	0.05
Dairy form[2]	-0.51	0.96	-1.47
Rump angle[2]	-0.32	0.07	-0.40
Thurl width[2]	-0.05	-0.38	0.33
Rear legs side view[2]	-0.20	0.47	-0.67
Rear legs rear view[2]	0.01	-0.40	0.41
Foot angle[2]	0.23	-0.51	0.74
Feet leg score[2]	0.19	-0.67	0.86
Fore udder attachment[2]	0.18	-0.96	1.13
Foot leg composite[2]	0.06	-0.52	0.57
Udder height[2]	-0.03	-0.37	0.34
Udder width[2]	-0.02	-0.80	0.79
Udder cleft[2]	0.35	-1.35	1.70
Udder depth[2]	0.01	-1.15	1.16
Teat length[2]	0.14	-0.95	1.09
TPI[1]	1007	949	58
Productive life (mo)[1]	-0.20	-1.16	0.96
SCS[1]	2.96	3.04	-0.08
Daughter pregnancy rate (%)[1]	0.17	-1.51	1.67
Calving ease[1]	8	9	-1
Milk persistency[3]	0.54	0.02	0.52
Fat persistency[3]	0.02	0.01	0.01
Protein persistency[3]	0.05	0.02	0.03

[1] Official evaluation source: Animal Improvement Programs Laboratory, USDA
[2] Official evaluation source: Holstein Association, USA, Inc.
[3] Unofficial evaluation source: Animal Improvement Programs Laboratory, USDA

Table 4.2: Summary of average state milk and heat tolerance PTA, rank of states based on milk and heat tolerant PTAs and number of cows included in the evaluation per state

State	PTA Milk	Rank milk	PTA heat tolerance	Rank heat tolerance	No. of cows
AZ	5.81	9	-0.08	35	75,598
CA	5.47	25	-0.07	17	1,323,034
CO	6.07	1	-0.07	17	46,175
CT	5.83	7	-0.06	7	36,307
FL	6.05	2	-0.09	39	29,557
GA	5.81	9	-0.07	17	52,789
IA	5.54	21	-0.07	17	183,526
ID	5.37	30	-0.06	7	101,481
IL	5.09	35	-0.05	3	118,272
IN	4.63	39	-0.05	3	90,219
KS	5.32	31	-0.07	17	67,890
KY	5.18	33	-0.06	7	39,211
LA	5.67	14	-0.07	17	21,690
MA	5.49	24	-0.05	3	27,818
MD	4.85	38	-0.03	1	98,078
ME	5.81	9	-0.06	7	32,063
MI	5.52	23	-0.08	35	256,684
MN	5.65	15	-0.07	17	518,473
MO	4.94	37	-0.06	7	63,559
MS	5.83	7	-0.07	17	22,373
NC	5.58	17	-0.07	17	69,746
NE	5.40	28	-0.07	17	56,821
NH	5.84	6	-0.07	17	26,917
NJ	4.97	36	-0.04	2	21,732
NM	5.86	5	-0.07	17	38,634
NY	5.54	21	-0.06	7	644,120
OH	5.40	28	-0.06	7	212,217
OK	5.55	20	-0.06	7	23,676
OR	5.61	16	-0.07	17	81,479
PA	5.24	32	-0.05	3	650,033
SC	5.57	19	-0.07	17	27,561
SD	5.44	27	-0.07	17	34,964
TN	5.58	17	-0.07	17	53,830
TX	5.96	3	-0.08	35	126,891
UT	5.47	25	-0.07	17	64,242
VA	5.78	12	-0.07	17	154,049
VT	5.76	13	-0.06	7	103,706
WA	5.88	4	-0.08	35	134,391
WI	5.18	33	-0.06	7	924,476

Figure 4.1: Trend of PTAs for daughter pregnancy rate (DPR) and heat tolerance by year of birth

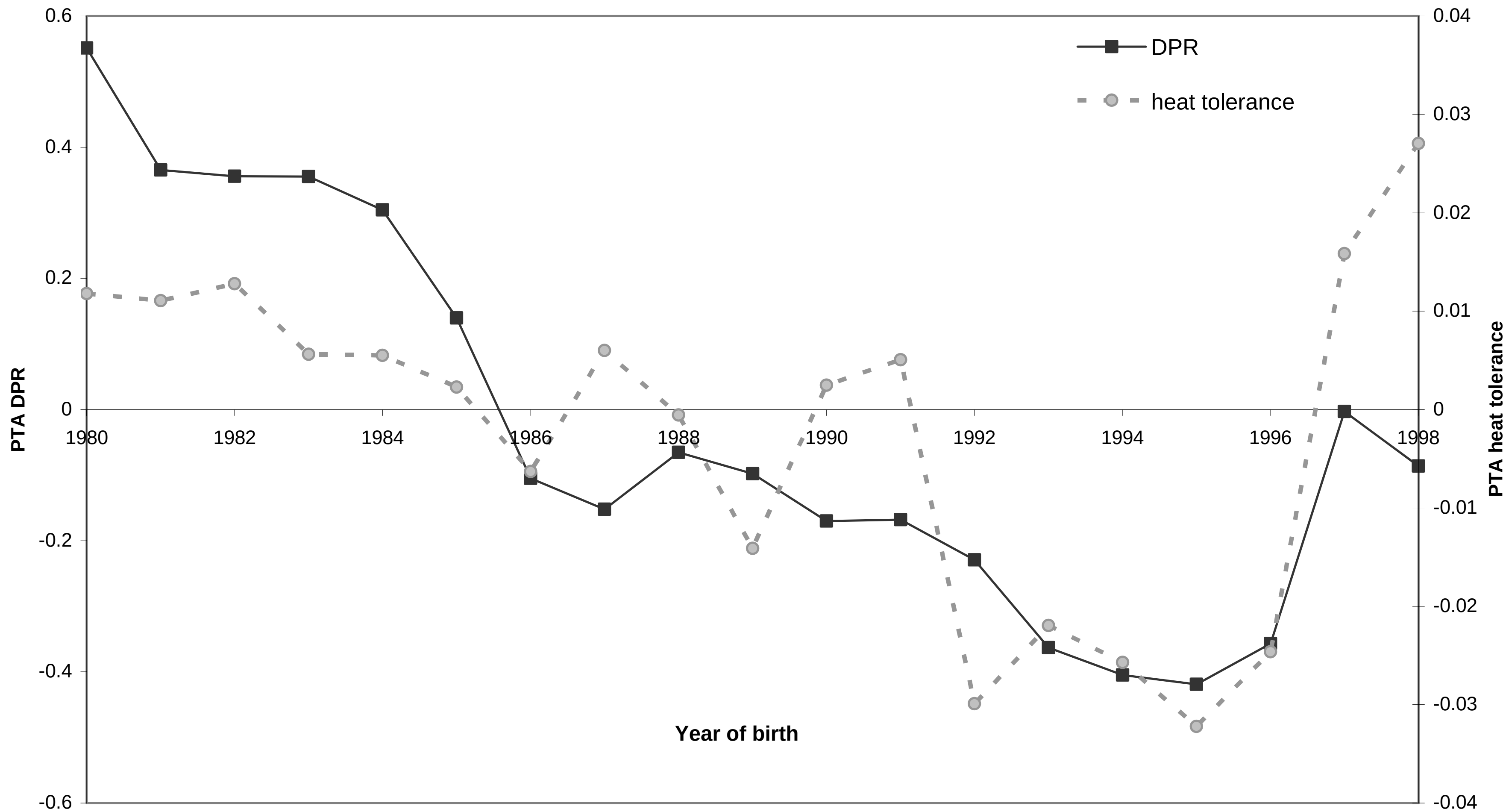
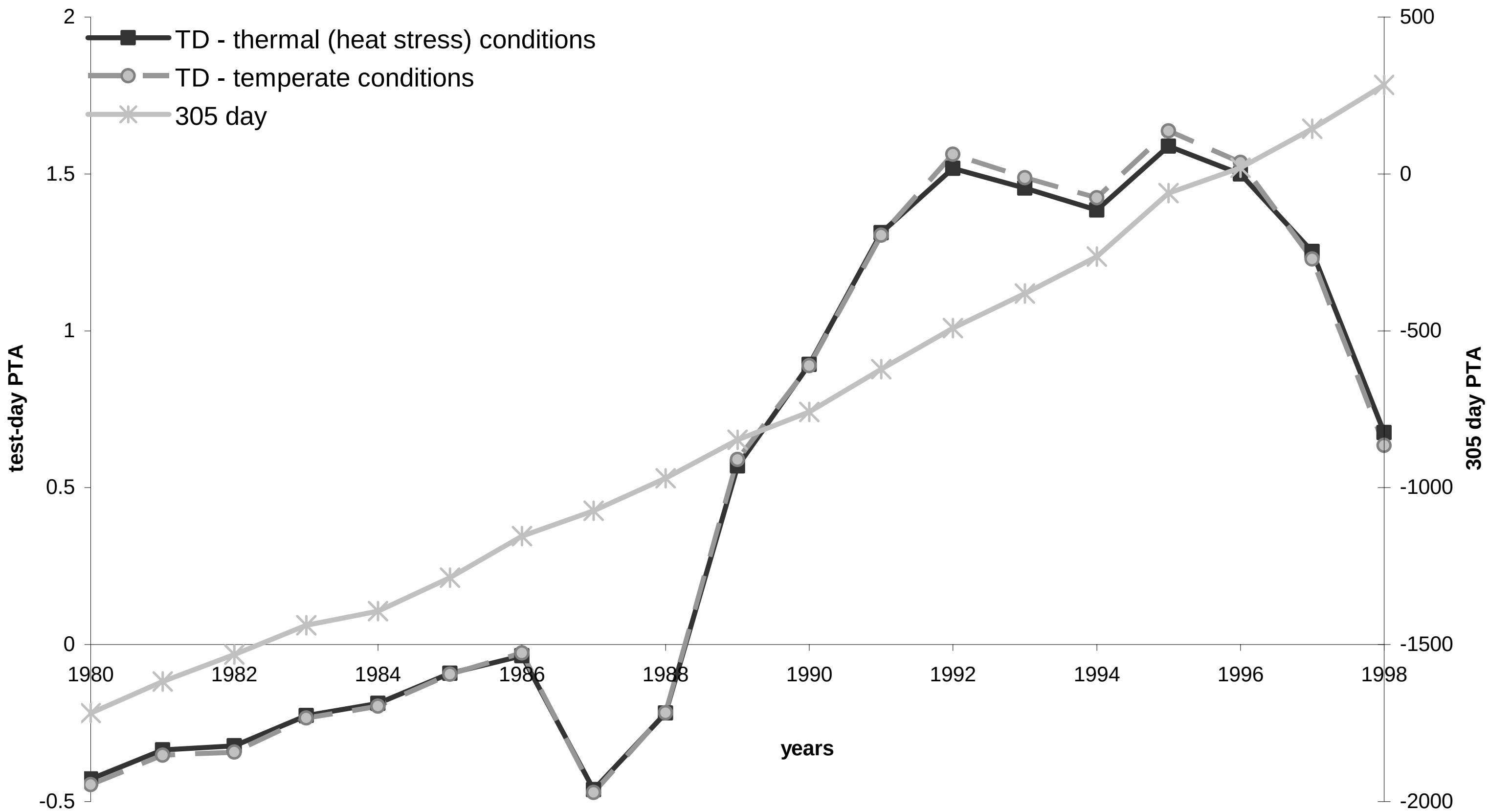


Figure 4.2: Trend of test-day PTA's in thermal and temperate conditions and 305 day PTA's by bull's birth year



CHAPTER 5

HEAT STRESS AS A FACTOR IN GENOTYPE X ENVIRONMENT INTERACTION IN U.S. HOLSTEINS

[1] J. Bohmanova, I. Misztal, S. Tsuruta, H.D. Norman, T. J. Lawlor. Submitted to *Journal of Dairy Science* 03/15/2006.

Abstract

Heat stress was evaluated as a factor in the genotype x environment interaction on milk production in the United States. The national data set (NA) consisted of 56 million first-parity test day milk yields on 6 million Holsteins. The Northeastern subset (NE) included 12.5 million records on 1.3 million cows from eight states, and the Southeastern subset (SE) included 3.5 million records on 0.4 million cows from eleven states. Climatic data were available from 202 public weather stations. Each herd was assigned to the nearest station. Average daily temperature-humidity index (avgTHI) three days prior to test date was used as an indicator of heat stress. Two test-day repeatability models were implemented. Effects in both models were herd-test date, age at calving class, frequency of milking, DIM x season class, additive genetic (regular breeding value) and permanent environmental effect. The second model additionally included random regressions on degrees of heat stress (t=max[0,avgTHI-72]) for additive genetic (breeding value for heat tolerance) and permanent environmental effects. Both models were fitted with the national and regional data sets. Correlations involved breeding values from SE and NE for sires with ≥ 100 and ≥ 300 daughters in each region. When heat stress was ignored (first model) the correlations of regular breeding values between SE and NE for sires with ≥ 100 (≥ 300) daughters were 0.85 (0.87). When heat stress was considered (second model), the correlation increased by 0.01. The correlations of heat stress breeding values between NE and SE for sires with ≥ 100 (≥ 300, ≥ 700) daughters were 0.58 (0.72, 0.81). Evaluations for heat tolerance were similar in cooler and hotter regions for high reliability sires. Heat stress as modeled explains only a small amount of G x E interaction, partly because test day records provide only snapshots of heat stress over a hot season.

(**Keywords**: genotype x environment interaction, reaction norm, heat stress)

Introduction

Dairy farming in the US is scattered over a wide range of climatic and topographic regions, and therefore presence of genotype by environmental (G x E) interaction and thereby re-ranking of sires in different regions of the United States can be expected. G x E interaction occurs when genetic correlation of a trait expressed in two different environments is lower than 0.8 (Robertson, 1959). The interaction can be modeled by different statistical models: 1) model with additional effect of genotype x environment interaction, 2) multitrait model defining records coming from different environments as a different trait, 3) model with genotype specific random regression on environmental variables – "reaction norm technique", where phenotype is expressed as a function of environmental descriptors (herd production level, herd size, temperature, humidity, and geographic position).

Large G x E interactions have been reported between countries with different climatic and production systems, such as New Zealand and United States (Weigel et al., 2001). However, most of within-country studies did not detect significant interactions. In the study of Carabaño et al. (1990), genetic correlations of milk production between New York, Wisconsin and California were all above 0.90 which seems to indicate little evidence for any significant G x E interaction across those states. Genetic correlations estimated by Rekaya et al. (2003) between five regions of the United States (Midwest, Northeast, Northwest, Southeast, and Southwest) were all larger than 0.93. The lowest genetic correlations were between Southeast and Southwest.

In general, differences between regional and national evaluations ($r<1.0$) can be explained either by limited accuracies in regional evaluations or due to regional differences in management and climatic conditions. Zwald et al. (2003) investigated effectiveness of thirteen genetic, management, and climatic variables in international dairy sire evaluation as indicators of production environments. Authors found lower heritability in herds from cool climates (0.26) than in herds from hot climates (0.39). Genetic correlations between those two groups were 0.86. This may suggest that heat stress plays an important role in G x E interaction.

In the study by Norman et al. (2005), correlations between national and regional evaluations for first parity milk yield ranged between 0.96 (Northeast) and 0.88 (Southeast). Lowest correlations with Southeast were probably caused by lower number of records in Southeast and also by much larger impact of heat stress on milk production losses in this specific region. Regional evaluation may be more or less accurate within a specific region than national evaluation because on one hand it accounts for the effect of genotype by region interaction but on the other hand it uses less data.

Ravagnolo and Misztal (2000) proposed a model that accounts for heat stress using weather data from public weather stations. Their model had two genetic effects per animal, one corresponding to performance under mild conditions, and one corresponding to a rate of decline after crossing the threshold of heat stress. The model was first applied to test day milk yield in Georgia and then Florida (Ravagnolo and Misztal, 2002). The correlation between the two genetic effects was negative, and the genetic variance due to heat stress was substantial at high temperature humidity indices. Bohmanova et al. (2005) applied a similar model to the US national data. Comparisons using sire summaries indicated that heat tolerant sires had lower fluid milk, higher fertility and productive life, and average TPI. Sires used in the Southeast were below average for heat tolerance due to the prevalence of fluid milk pricing in the region. Therefore, problems of heat stress in the Southeast are increasing over time.

The aim of this study was to investigate importance of genotype x environment interaction in the US Holsteins, to determine if the effect of heat stress can explain a sufficient part of the differences between regional and national genetic evaluations, and to see whether sires rank the same for heat tolerance in different regions.

Materials and methods

Milk yield data

The data were obtained from AIPL/USDA and included first parity test day (TD) milk yields of Holsteins calved between 1993 and 2004. The National data set (NA) consisted of 55,494,545 TD records on 5,797,297 cows. The Southeast and the Northeast were defined as in Norman et al. (2005). The Northeastern data set (NE) included 12,505,982 TD records from CT, MA, ME, NH, NJ, NY, PA and RI on 1,293,429 cows. The Southeastern data set (SE) included 3,451,223 TD records from AR, AL, FL, GA, LA, MS, NC, OK, SC, TN, TX on 357,130 cows. All TD records were required to be between 5 and 365 DIM. More detailed description of the data is given in Table 5.1. As presented in Figure 5.1, the majority of records in SE originated from Texas (31%), North Carolina (16%), Georgia (12%), Tennessee (11%) and Florida (7%). The majority of records in NE (85%) originated from New York (44%) and Pennsylvania (41%), viz. Figure 5.2.

Meteorological data

Hourly meteorological data (temperature and relative humidity) were available from 202 public weather stations across the United States. Temperature humidity index (THI) was determined from temperature in °C (temp) and relative humidity in % (rh) as follows (National Research Council, 1971):

$$THI = [1.8*temp + 32] - [0.55 - 0.0055*rh)][1.8*temp - 26]$$

Hourly THI were rounded to the nearest whole number and averaged over 24 h to obtain average daily THI. Average daily THI three days prior (avgTHI) to the test date was assigned to each test day record from the nearest weather station and the threshold of heat stress was set to avgTHI of 72 for all herds. The choice of a three day lag between weather and yield test day was based on results from a separate unpublished study, where it was shown that weather data three days prior to the test date explained more variability than weather data one or two days prior to the test day or on the test day. Level of heat stress on the farm depends on many factors, including the use and type of cooling devices. However, this information was not available.

Heat stress degree (t) was used to estimate decline of milk production caused by heat stress. Heat stress degree was defined as a sum of units of avgTHI above 72. Therefore

if avgTHI $\leq$ 72 *then* t=0 (no heat stress)

else if avgTHI>72 *then* t=avgTHI-72

Sum of yearly heat stress degrees were calculated for every public weather station and used as a description of thermal conditions in individual states. As given in Table 5.2, Florida, Louisiana and Texas are the states with highest heat stress degrees per year in the United States, with 916, 818 and 761 heat stress degrees per year, respectively. Looking at regions, the Southeast has on average 596 heat stress degrees per year compared to 88 in the Northeast. National average is 239.

As shown in Figure 5.3, 10, 7, and 27% of TD records were obtained on days with thermal stress (avgTHI > 72) in NA, NE and SE. In SE, 14% of TD records were measured on moderate heat stress days (73 $\leq$ avgTHI $\leq$ 76) and 13% on severe heat stress days (avgTHI > 76).

Models

Two repeatability models were employed for national and regional genetic evaluations of test-day milk yields.

<u>*Standard model:*</u>

$$y_{ijklmnr} = htd_i + age_j + freq_k + dim_{lm} + a_n + p_r + e_{ijklmnr}$$

where htd_i is the fixed effect of the i^{th} herd-test date, age_j is the j^{th} age at calving class (j=1 to 8), $freq_k$ is k^{th} frequency of milking (k= 1 to 4), dim_{lm} is the l^{th} DIM class (j=1 to 37), with classes defined every 10 days, nested within season m (m=1 to 4; December to February, March to May, June to August, September to November). a_n is the generic additive genetic effect for animal n, p_r is the permanent environmental effect for animal r, and $e_{ijklmnr}$ is residual.

The variance covariance structure was:

$$\text{var}\begin{bmatrix} a \\ p \\ e \end{bmatrix} = \begin{bmatrix} A\sigma_a^2 & 0 & 0 \\ 0 & I_r\sigma_p^2 & 0 \\ 0 & 0 & I_s\sigma_e^2 \end{bmatrix}$$

where A (n x n) is an additive relationship matrix and I_r is an identity matrix of size r x r for the permanent environmental effect, I_s is an identity matrix of size s x s for the residual (s is the number of TD records) and σ_a^2=26.45, σ_p^2=45.98 and σ_e^2=76.49.

<u>*Expanded model:*</u>

To account for genetic differences in heat tolerance, additional random regressions on degrees of heat stress were included in the following model:

$$y_{ijklmnr} = htd_i + age_j + freq_k + dim_{lm} + a_{0n} + a_{1n} \times t + p_{0r} + p_{1r} \times t + e_{ijklmnr}$$

where a_{0n} is the additive general genetic effect independent of level of heat stress, indicating animal's ability to produce milk in thermoneutral conditions, a_{1n} is the additive genetic linear random regression coefficient of heat tolerance for animal n, describing animal's environmental sensitivity to thermal stress, p_{0r} is the permanent environmental general effect (the basic level), and p_{1r} is the permanent environmental random regression effect (slope) of heat tolerance for animal r.

The variance covariance structure was:

$$\mathrm{var}\begin{bmatrix} a_0 \\ a_1 \\ p_0 \\ p_1 \\ e \end{bmatrix} = \begin{bmatrix} A\sigma_a^2 & A\sigma_{a\alpha} & 0 & 0 & 0 \\ A\sigma_{a\alpha} & A\sigma_\alpha^2 & 0 & 0 & 0 \\ 0 & 0 & I\sigma_p^2 & I\sigma_{p\pi} & 0 \\ 0 & 0 & I\sigma_{p\pi} & I\sigma_\pi^2 & 0 \\ 0 & 0 & 0 & 0 & I\sigma_e^2 \end{bmatrix}$$

where σ_a^2=26.74, $\sigma_{a\alpha}$=-0.89, σ_α^2=0.16, σ_p^2=46.46, $\sigma_{p\pi}$=-1.17, σ_π^2=0.04 and σ_e^2=76.33.

State specific test day breeding values were calculated from the generic (a_0) and heat tolerance (a_1) breeding values from the national genetic evaluation as follows:

$$a_j = a_0 + a_1 \times \left(\sum_{i=1}^{365} t_{i,j}\right)/365$$

where $\left(\sum_{i=1}^{365} t_{i,j}\right)$ is the average number of heat stress degrees per year in the state j (viz. Table 5.2).

Breeding values were estimated by BLUPIODF90 (Tsuruta et al., 2001), a program that handles large data sets using iteration on the data technique with a preconditioned conjugate gradient algorithm.

Results and discussion

As shown in Table 5.3, 636 sires had ≥ 100 daughters in both NE and SE. Those sires had on average 6,171, 1,413 and 487 daughters in NA, NE and SE, respectively. A second group of 265 sires with ≥ 300 daughters had on average 10,344, 2,310 and 889 daughters in NA, NE and SE, respectively.

Table 5.4 shows correlations of predicted breeding values between national and regional genetic evaluations for the two sire groups and the two models. For the ≥ 100 (≥ 300) daughters group using the standard model, the correlations were 0.87 (0.89) in SE and 0.96 (0.97) in NE. This is similar to correlations of 0.88 and 0.97 obtained by Norman et al. (2005). Correlations increased with the number of daughters per sire. Correlations between SE and NE increased from 0.87 to 0.89 when the number of daughters increased from 100 to 300; the correlations for the predicted breeding values are dependent on sire accuracies. When the heat stress effect was added to the model, those correlations increased by 0.005 in the ≥ 100 daughters group and by 0.009 in the ≥ 300 daughters group. The change was in the expected direction but small, indicating that adding the heat stress effect in the model does not greatly increase the correlations between the regular breeding values as expected. Several explanations are possible: a) presence of G x E interaction due to reasons other than heat stress, b) inadequate model, c) inadequate weather records, and d) inadequate production data. Freitas et al. (2005) found that response to heat stress based on test days was about ⅓ that obtained with daily records. This is because the effect of heat stress between the test days cannot be considered and because only a few observations per year are used to model variation in cooling over time. Also, the model as used in this study captures instantaneous but not long-term response to heat stress. Assuming that only ¼ of response to heat stress has been captured in the model with test days, heat stress likely accounts for a substantial if not the majority of the G x E interaction. To capture more of the heat stress effect would require more frequent test days.

Table 5.4 also lists the genetic correlations between the NE and SE for the heat stress breeding value. The correlation increased from 0.58 to 0.72 as the number of daughters per sire increased from 100 to 300. When sires with ≥ 700 daughters were considered the correlation reached 0.81. Thus the analyses in both regions identified similar heat tolerant sires but only for sires with high accuracy. Since only a fraction of variability of heat stress is captured with the test-day data, it requires a large number of records to have a reasonable accuracy. That accuracy is also a function of the amount of heat stress in a particular region. More heat stress information per cow is available in data collected in the SE than in the NE, however, the number of cows in the NE is much larger.

Table 5.5 shows genetic correlations between predicted breeding values in several states assuming average number of daily heat stress degrees per particular state (Table 5.2) and either the heat tolerance values as computed in NA or four times larger. The last case assumes that only ¼ response of heat stress has been captured in the model of this paper. When heat tolerant breeding values are as computed, the correlation between compared states are all > 0.99. However, with heat stress breeding values four times larger, the correlations between Southeast and Northeast is < 0.99. Florida, the hottest state in Southeast, has correlation < 0.90 with NE. This correlation would likely to be much lower if response to heat stress was not masked by management strategies, such as use of heat abatement devices and timing calving to avoid the peak of production during the hot season.

Conclusions

Breeding values for heat tolerance calculated in different regions are similar. A national evaluation for heat stress is possible. However, accuracies of breeding values for heat tolerance for most bulls are low, and only a small fraction of variability due to heat stress may be explained by the model used. Therefore only well proven bulls will have reliable evaluations for heat stress. More information on effects of heat stress can be captured with records tested more frequently than monthly.

Acknowledgments

The authors thank J. B. Cole from Animal Improvement Programs Laboratory, USDA (Beltsville, MD) for providing the weather data. This study was supported by 58-1265-3-161 grant from AIPL/USDA.

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Table 5.1: Summary statistics of national and regional data sets

	National	Northeast	Southeast
Number of first parity test day records	55,494,545	12,505,982	3,451,223
Number of cows	5,797,297	1,293,429	357,130
Average milk yield (kg)	29.1	28.3	27.4
Variance of milk yield (kg^2)	54.8	53.9	54.0
Average number of primiparous cows per herd	21	16	25
Number of sires	160,058	59,921	28,126

Table 5.2: Number of weather stations per state, average (Mean), minimal (Min), maximal (Max) and standard deviation (SD) of yearly heat stress degrees per state

State	Number of weather stations	Heat stress degrees per year				Region
		Mean	Min	Max	SD	
AL	3	439	346	533	93	Southeast
AR	2	562	542	582	28	Southeast
AZ	2	701	480	922	312	-
CA	8	95	0	333	126	-
CO	3	6	0	14	7	-
CT	2	96	79	113	24	Northeast
DE	1	189	189	189	-	-
FL	8	916	637	1427	290	Southeast
GA	6	452	320	616	112	Southeast
IA	4	122	84	166	34	-
ID	3	24	3	40	19	-
IL	5	152	93	202	43	-
IN	4	165	100	295	92	-
KS	4	285	193	364	75	-
KY	5	216	113	331	101	-
LA	4	818	696	938	120	Southeast
MA	2	60	30	91	43	Northeast
ME	3	81	9	212	114	Northeast
MI	7	53	18	99	25	-
MN	5	37	9	83	30	-
MO	4	289	233	375	63	-
MS	3	498	446	555	54	Southeast
MT	5	2	0	9	4	-
NC	5	265	27	501	172	Southeast
ND	3	32	18	44	13	-
NE	7	124	13	214	77	-
NH	1	32	32	32	-	Northeast
NJ	2	183	156	210	38	Northeast
NM	1	23	23	23	-	-
NV	4	133	0	520	258	-
NY	5	42	16	51	15	Northeast
OH	7	89	45	137	32	-
OK	2	492	434	551	83	Southeast
OR	7	7	0	16	7	-
PA	7	111	46	247	73	Northeast
RI	1	82	82	82	-	Northeast
SC	3	443	250	609	181	Southeast
SD	4	68	22	97	36	-
TN	5	313	64	575	186	Southeast
TX	12	761	214	1324	332	Southeast
UT	1	47	47	47	-	-
VA	7	207	40	385	118	-
WA	5	5	0	16	7	-
WI	5	71	43	105	25	-
WV	4	69	12	141	62	-
WY	4	2	0	5	2	-

Figure 5.1: Proportional distribution of test day records in the Southeastern data set by state

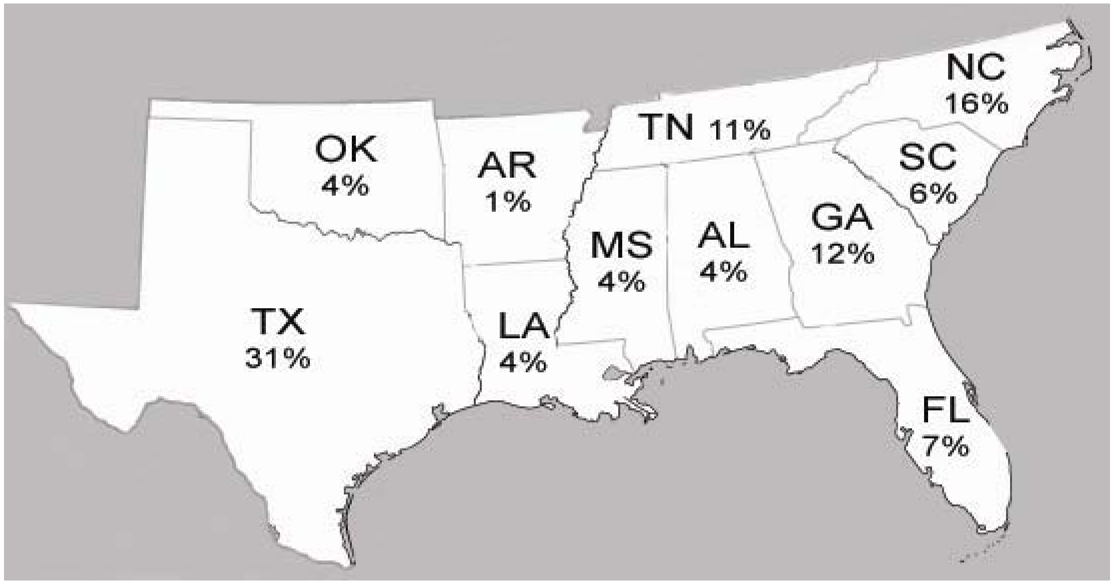

Figure 5.2.Proportional distribution of test day records in the Northeast data set by state

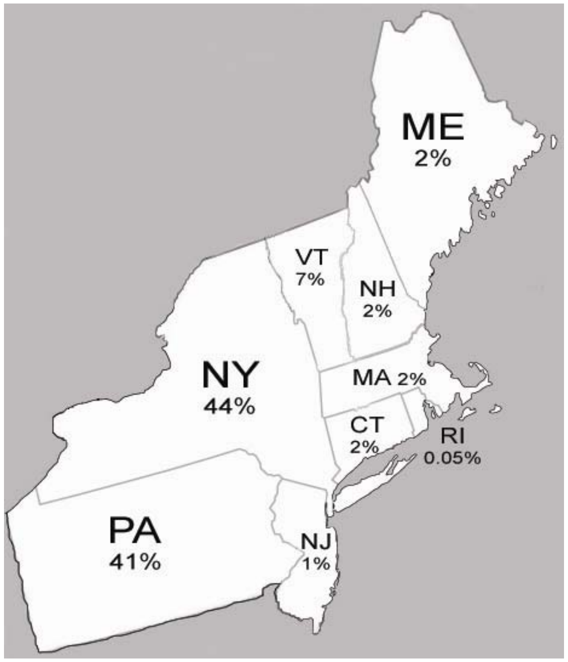

Figure 5.3: Frequency of test day records with no heat stress (avgTHI <72), moderate heat stress (73 ≤ avgTHI ≤ 76) and severe heat stress (avgTHI > 76) in National, Northeast and Southeast data set

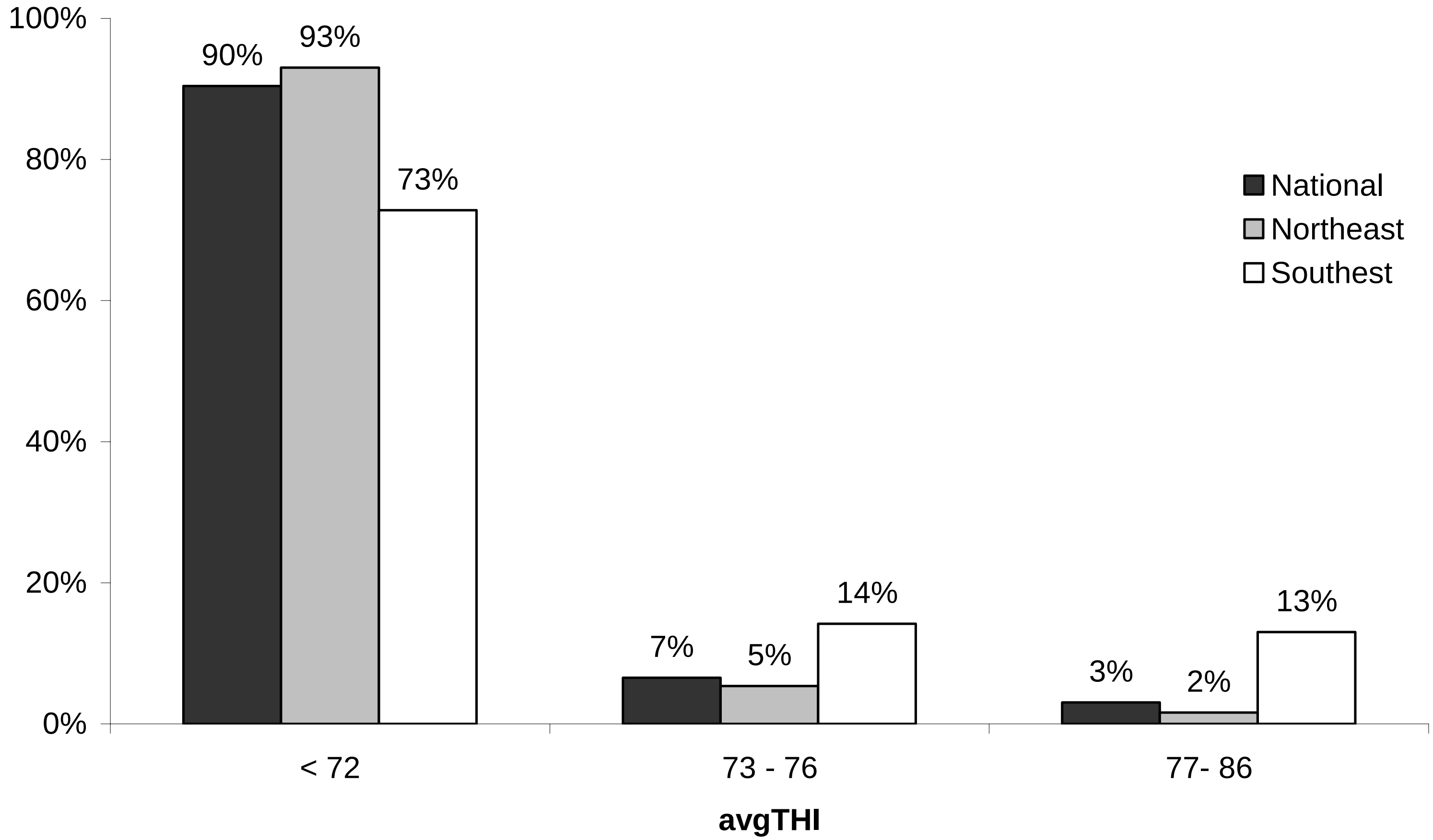

Table 5.3: Average number of daughters per sire for 636 sires with ≥ 100 daughters and for 265 sires with ≥ 300 daughters in National, Northeast and Southeast data set.

		Mean number of daughters		
	No. sires	**National**	**Northeast**	**Southeast**
≥100 daughters group	636	6,171	1,413	487
≥300 daughters group	265	10,344	2,310	889

Table 5.4: Spearman correlations of sire's breeding values for heat tolerance additive effect ($Corra_{1\_GE}$), generic additive effect ($Corr_{a0\_GE}$) using the Expanded model and generic additive effect ($Corr_{a\_G}$) using the Standard model between Southeast (SE), Northeast (NE) and National (NE) data sets; differences in correlations of generic additive effects from the Expanded model and the Standard model ($Corr_{a0\_GE}$ - $Corr_{a\_G}$)

	$Corr_{a1\_GE}$			$Corr_{a0\_GE}$			$Corr_{a\_G}$			$Corr_{a0\_GE} – Corr_{a\_G}$		
Sires	**SE x NE**	**SE x NA**	**NE x NA**	**SE x NE**	**SE x NA**	**NE x NA**	**SE x NE**	**SE x NA**	**NE x NA**	**SE x NE**	**SE x NA**	**NE x NA**
≥ 100[7]	0.575	0.789	0.774	0.845	0.873	0.962	0.840	0.871	0.961	0.005	0.002	0.001
≥ 300[8]	0.715	0.880	0.847	0.874	0.896	0.970	0.864	0.891	0.970	0.009	0.004	0.000

[7] Sires with ≥ 100 daughters in both NE and SE

[8] Sires with ≥300 daughters in both NE and SE

Table 5.5: Spearman correlations of original (as estimated in NA), and altered[9] state specific breeding values (breeding values for heat stress four times larger - in parentheses)

	Southeast			Northeast
	FL	**GA**	**TX**	**NY**
GA	1.00 (0.95)			
TX	1.00 (0.99)	1.00 (0.98)		
NY	0.99 (0.86)	1.00 (0.97)	0.99 (0.91)	
PA	0.99 (0.88)	1.00 (0.98)	0.99 (0.92)	1.00 (1.00)

[9] Assumes four times underprediction of heat tolerant breeding values in the model

CHAPTER 6

CONCLUSIONS

The results from this study indicate that test-day milk yield records in combination with meteorological data from public stations provide a valuable source of information for genetic evaluations of heat tolerance. Heat stress is more effectively alleviated by various modifications of environment in Phoenix, AZ than in Athens, GA, mainly because the humid climate in Athens compromises efficiency of evaporative cooling devices. In dry climates ambient temperature plays more important role than humidity. In humid climates, the amount of moisture in the air is a more important factor than ambient temperature.

Sires with higher tolerance to heat stress transmit lower milk yields with higher fat and protein contents. Their daughters have better udders and type, lower dairy form, slightly higher TPI, longer productive life, higher daughter pregnancy rate, easier calving and better persistency than daughters of sires that are more sensitive to heat stress. Continued selection for milk yield without considering heat stress can result in animals with lower heat stress tolerance.

Heat stress explained only a small portion of genotype by environment interaction between temperate and thermal regions. However, the effect of heat stress could have been much larger if it was not masked by evaporative cooling. Moreover, the model as used in this study identifies only the response due to the acute (immediate) and not the chronic (long-term) thermal stress. Daily milk yield records could be a valuable source of data for more accurate evaluation of heat stress. Daily records provide enough information which would allow to account for use of cooling devices (identify threshold of heat stress at a herd x year basis) and identify response to both short and long-term effects of heat stress. Nevertheless, the use of daily records for genetic evaluation for heat tolerance is currently prevented by limited availability of the records.