Modelling heat stress and water loss of beef cattle in subtropical Queensland under current climates and climate change

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Abstract The possibility of global warming suggests that existing heat stress on livestock in tropical and subtropical Australia may increase and that demands for water may also increase. We investigate two different models for assessing heat stress in beef cattle: one is an empirical temperature-humidity index (THI) with simple daily meteorological inputs and the other is based on a complex multi-layered physical representation of an animal which calculates hourly energy and water transfers between the animal and the environment. This second approach calculates evaporative heat losses and these losses when combined with other information on water fluxes such as urine allows water requirements to be calculated via a mass balance approach. These models were run on a climate data set for Gayndah in south-east Queensland for the years 1957-1996. In addition a climate change scenario was constructed by raising both the minimum and maximum temperatures by 2.76°C which is a mid-range temperature change for approximate doubling of atmospheric greenhouse gas concentrations. We found that the model provides acceptable estimates of the water requirements of Brahman beef cattle and that mean air temperature dominated this response. The empirical model was more strongly correlated with water requirements than the physically-based model. However, both models gave similar representations of the incidence of heat stress in cattle. The incidence of stress days as measured by THI greater than 80 has increased significantly over the 40 year period (~60%) and the climate change scenarios suggested further, substantial increases (138%) in the frequency of such heat stress days. In addition, in the climate change scenario there was a very marked increase (from zero to 92 days in the record) in days where animals could no longer thermoregulate by sweating alone. Water requirements are likely to increase by around 13% under the climate changes simulated. These results suggest that further selection for cattle lines with effective thermoregulatory control will be needed in the future, however it may be difficult to combine the desirable traits of adaptation to high temperature environments with high production potential in cattle. Model limitations and development needs are discussed.

1. INTRODUCTION

Heat stress is a significant issue for livestock grazing in tropical areas of Australia and these stresses are likely to increase with prospects of global warming due to the accelerating emission of greenhouse gases (eg Houghton et al. 1996). Heat stress in livestock has been reported to decrease conception rates and increase foetal and postnatal mortalities (Finch 1983; Berman 1991), impair spermatogenesis (Entwhistle 1992) increase urinary nitrogen loss (O'Kelly 1988) and increase susceptibility to a range of parasitic and non-parasitic diseases (eg Finch 1983). Heat stress has also been found to decrease growth rates (eg Frisch 1981, Hahn 1985) although there appears to be strong compensatory growth responses when animals are returned to less stressful conditions following drought (G. McKeon unpublished data). High heat loads also result in greater water requirements for livestock (eg King 1983). Lack of availability of water due to the large distances from water sources that tropical animals sometimes have to forage, can reduce production directly through reductions in metabolic rates and feed intake (eg Utley 1970) and indirectly by reducing the area grazed through restriction of distance travelled from watering points (eg Noble 1975).

Heat stress in cattle has been analysed using two main approaches. Firstly through the use of relationships such as the Temperature-Humidity Index (THI; Johnson *et al.* 1963) which relates stress to both daily maximum temperature and dewpoint temperature. This relationship, originally derived for dairy cattle with high intake and metabolic rates, has been shown to be a robust predictor of heat stress in cattle being related to reduced milk production in dairy cattle (Hahn and Oosburn 1969), conception rates (Hahn 1981) and mortality rates (Hahn 1985), distribution of beef cattle varieties in Africa (King 1983) and operational use for heat stress assessment in dairy cattle in South Africa (Du Preez *et al.* 1990). The THI has minimal input requirements and has been used in a variety of environments which makes it suitable for broad scale assessment of issues such as climate change impacts. However, King. (1993) and Finch (1983) suggest that effective evaluation of the implications of heat stress for beef cattle in extensive grazing systems requires additional measurements of net radiation load and convection. Furthermore, the THI approach does not explicitly incorporate important factors such as coat colour which influence heat loads and thus provides little information on how to direct selection programs to enhance heat loss mechanisms (Finch 1983). An alternative approach is to explicitly model fluxes of water and energy from animals using a physically-based approach such as that in Turnpenny et al. (1997). However, this approach requires considerable parameterisation information and intensive data input (ie hourly meteorological variables) which are often not available.

The second approach explicitly models evaporation from the skin surface of livestock. This provides the possibility of modelling water requirements of livestock by using a mass balance approach which accounts for other water gains (eg in feed) and losses (eg urine).

The aim of this study was to compare the two approaches to analysing heat stress on livestock, to develop an approach for modelling water requirements of livestock in the Australian tropics and to investigate how both heat stress and water requirements are likely to change with climate change.

2. HEAT STRESS MODEL DESCRIPTIONS

The THI is calculated as:

$$\mathrm{THI} = T_{max} + 0.36T_{dewpoint} + 41.2$$

where T_{max} is daily maximum dry bulb temperature (°C) and $T_{dewpoint}$ is dewpoint temperature (°C)

A series of mathematical models were developed to predict the metabolic rate and occurrence of thermal stress in different livestock species (Turnpenny 1997). The models calculate heat loss from model animals using hourly meteorological data as input and assess the degree of thermal stress under different combinations of weather conditions. The models were designed to be applicable to as wide a range of conditions as possible, and as such have been based on animal physiology and the physics of heat transfer rather than empirical relationships.

The model for beef cattle was developed as a system of cylinders with rounded ends, and incorporates three layers - the underlying tissue, the coat and the external environment. By specifying the thermal environment, metabolic rate and weight of the animal, the temperatures of the layer interfaces are calculated by solving the energy balance at each interface. This allows the heat loss from the cow to be calculated. Physiological responses to heat and cold stress, including sweating and varying blood flow to the peripheries have been parameterised. Further details of the general energy balance model are in Turnpenny et al. (1997), and a more in-depth discussion of considerations for outdoor animals, such as shade and shelter requirements can be found in Turnpenny (1997). The beef cattle model is described briefly in Parsons et al. (1997). The model uses hourly data for the environmental inputs which were downscaled from daily climate data using the approach of Armstrong et al. (1997) and Turnpenny (1997). Briefly, hourly values of the following variables: cloud cover fraction, direct and diffuse components of solar radiation, air temperature, radiant temperature of the sky, ground temperature, precipitation were calculated from daily observations of temperature, rainfall, vapour pressure and incident solar radiation. Solar radiation is generated by comparing the top of the atmosphere total radiation with the measured total, and deducing an atmospheric transmittance which is related to cloud cover fraction. The direct and diffuse components for each hour are then calculated empirically. Air temperature is a sine function between the maximum and minimum, with the maximum occurring at 2 pm, and the minimum at 2 am. Sky temperature is an empirical function of cloud cover and air temperature and ground temperature is found by solving a simple energy balance. Vapour pressure is assumed constant over the day. Wind speed data were not available, so a typical value of 2 m s^{-1} was used for all times. Precipitation was distributed using a triangular function centred on midday.

Brahman (*Bos indicus*) cattle are now widely used throughout the Australian tropics. Their efficient sweating responses providing superior thermoregulatory ability over those of *Bos taurus* breeds (Finch *et al.* 1982) for which the heat loss model was originally parameterised. The model has been re-parameterised for Brahman cattle using information in Finch *et al.* (1982,1984). The simulations reported here were for a 425kg animal and key parameter changes for these simulations were thermoneutral heat production of 600W, coat albedo 0.5 and 15mm coat depth on the body and 3mm on head and legs.

3. WATER REQUIREMENT MODEL

Cattle have a very efficient sweating mechanism which increases heat loss when the conditions are too hot for the metabolic heat production and heat gain from the environment to be dissipated by sensible heat alone, and under hot conditions a 500 kg cow can lose up to a litre per hour through sweating alone (Thompson, 1973; Webster, 1974). The thermal balance model above calculates the evaporative water flux (E) from the skin given the environmental conditions. This flux can then be combined with estimates of water gain from metabolic water production (M), water in the feed (F) and water in the urine (U) and faeces (F) in a water balance approach to calculate water intake:

$$\text{Water intake (l/day)} = E + U + F - M - F$$

F depends on the feed intake per unit time, and the water content of the forage, which can vary from 0% to more than 80% of dry matter (DM) depending on the weather conditions and species (Wood et al. 1996) and was assumed to be a constant 35% with an intake of 12 kg DM/day (for the 425kg animal modelled here). M was modelled as a linear function of the total metabolic heat production (600 W for a 425kg animal) following Brown and Lynch (1972). The fraction of water intake lost as urine and faeces remained constant at 32% and 35% respectively following the results of Colditz and Kellaway (1972) for Brahman cattle in tropical Australia under a range of temperature conditions. Additional water is needed if there is high salt concentrations in the diet, however, this tends not to happen in tropical Australia whilst it is an issue in the saltbush (*Atriplex* sp.) shrublands of temperate Australia.

4. MODELLING STUDIES

The two approaches for calculating heat stress indices were tested for one site (Gayndah, Qld.,25.7°S, 151.8°E) in subtropical Australia for the forty years 1957-96. Daily climate data for maximum and minimum air temperatures, rainfall, evaporation, total solar radiation on a horizontal surface and vapour pressure were retrieved from climate surfaces (Carter et al. 1996) and then downscaled to hourly data for the physically-based approach.

To enable comparison with the THI, a daily heat stress index was constructed from the physically-based model by averaging the calculated ratio between hourly evaporative flux density and the maximum evaporative flux for the five hours from 11am to 3pm.

Daily modelled water intake was compared with daily maximum temperatures to enable comparison with observed intake data and to compare with the relationship of King (1983) for the years 1957 (driest year of the record - 220mm) and 1959 (wettest year - 945mm). These years were chosen as they represent the extremes available in this 40 year record. The THI was compared with the stress index for all years and the calculated water intake was compared with both indices.

Thermal stress is likely to occur in beef cattle when THI exceeds a value of 80 (D. Mayer pers. comm.). Regression analysis was used to determine if there was any trend of change in the frequency of days/year with THI over a threshold of 80 during the past 40 years.

A climate change scenario (2xCO_2) was constructed based on the Australian 1996 CSIRO scenarios (http:/www.dar.csiro.au/pub/programs/climod/cm4.htm) for a doubling of atmospheric CO_2 concentration for the mid-range emissions scenarios and mid-range climate sensitivities. This suggested a 2.76°C increase in temperatures in this location happening around the year 2100. The historical temperature record was modified by increasing both the daily maximum and minimum temperatures and then recalculating the hourly data. The climate change scenarios also suggest rainfall changes (summer -24% to 0% and winter -12% to 12%) however these were not included in these simulations as they are likely to have secondary impacts compared with the temperature and associated changes.

5. RESULTS

Simulated daily water requirements were highly correlated with daily mean temperatures for both the wettest and driest years on the climate record used (eg Figure 1). There was no significant difference between the regressions ($p < 0.001$) for the two years with a pooled regression being:

Water requirement (l/day) = 1.30 T_{mean} - 1.59

Simulated water requirements using this regression were 20.5, 29.6, 40.0 and 47.8 litres/day for 17°C, 24°C, 32 °C and 38 °C respectively. Measured values of water requirements for Brahman cattle in controlled temperature rooms are 30, 36, 38 and 44-49 litres/day for the above temperatures (Colditz and Kellaway 1972, O'Kelly and Reich 1981) indicating good agreement at temperatures of 32°C or higher.

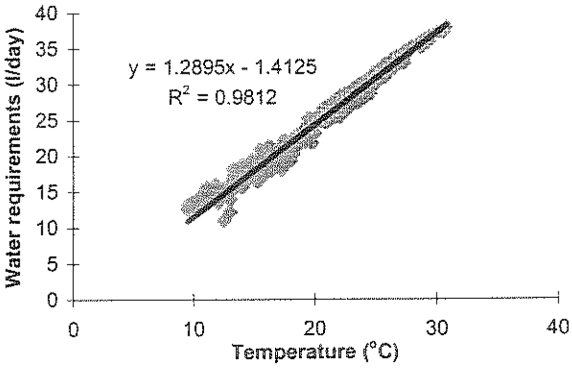

Figure 1. Variation of simulated water requirements (l/day) with daily mean temperature (°C) for Gayndah for the year 1957.

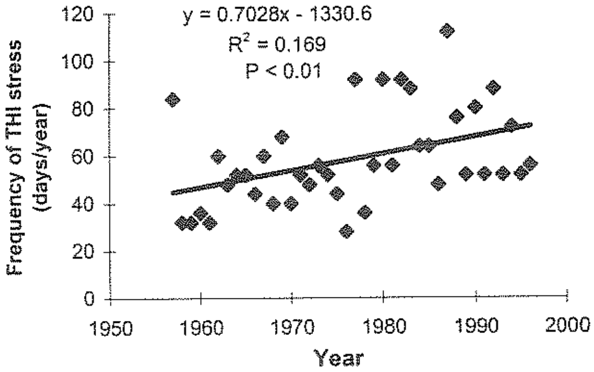

Figure 2. Annual frequency of days when THI greater than 80 for the years 1957-1996.

There were strong linear relationships between the daily THI values and the stress index calculated from the physically-based model (Fig. 3: $r^2 = 0.84$) and between simulated water requirements and THI (Fig. 5: $r^2 = 0.96$). The relationship between water requirements and the stress index (Fig. 4) was less strong ($r^2 = 0.74$) with significant variation due to other factors such as solar radiation, evaporation and vapour pressure.

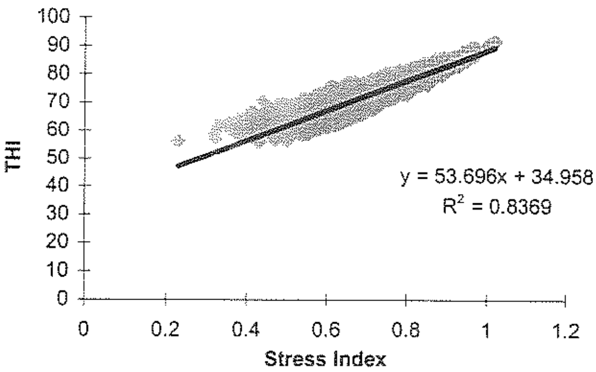

Figure 3. Relationship between daily THI and the daily stress index from the physically-based model.

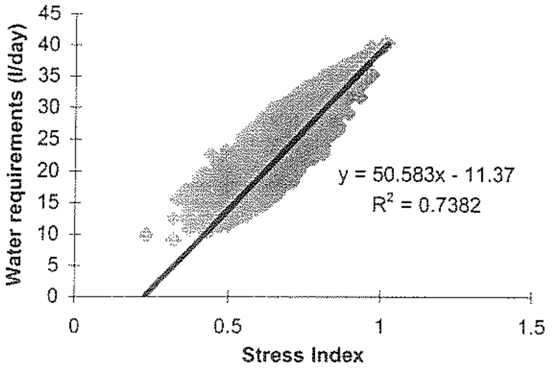

Figure 4. Relationship between simulated daily water requirements and the daily stress index from the physically-based model.

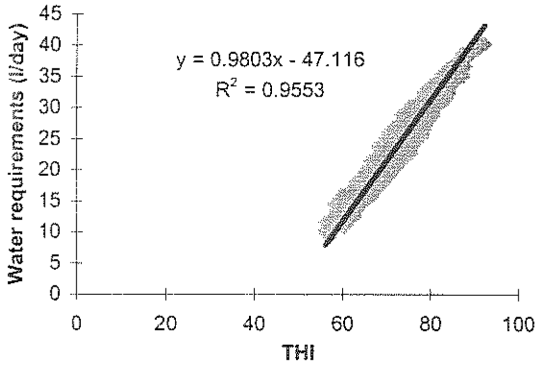

Figure 5. Relationship between simulated daily water requirements and daily THI.

The incidence of days that exceeded a THI threshold value of 80 has increased significantly ($P < 0.01$) during the past 40 years (Fig. 2) with the regression being:

Frequency (days/year) = 0.7028*year - 1331 ($r^2 = 0.17$)

Inspection of the data showed that high frequencies of days exceeding the threshold occurred in drought years.

Median water requirements were increased by about 13% under the climate change scenario compared with current conditions (Fig. 6) whilst this increase was only 7% for the stress index (Fig. 7) and 5% for the THI (Fig. 8). However, in the climate change scenario there were 92 days where the heat stress index exceeded a value of 1 whereas there were no days which this occurred in the current climate scenario. Stress index values greater than unity mean that the cattle can no longer thermoregulate via sweating alone and that they need to either start to pant or adopt behavioural changes (ie seek shade or stand head-on to the sun) to avoid hyperthermia. In contrast the highest stress index value for current climate condions was 0.92.

The THI threshold value of 80 was exceeded on only 16% of days under the current climate. Under the climate schange scenario this occurred on 38% of days.

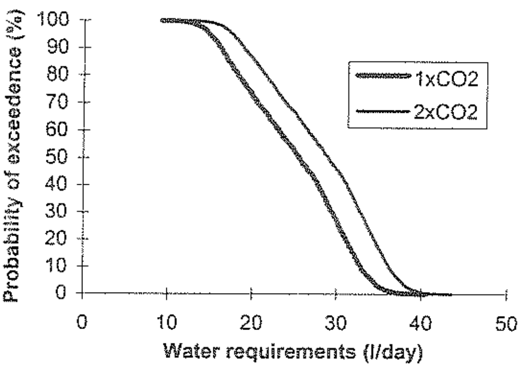

Figure 6 Probabilities of exceedence of water requirements (l/day) under the current climate and with the climate change scenario.

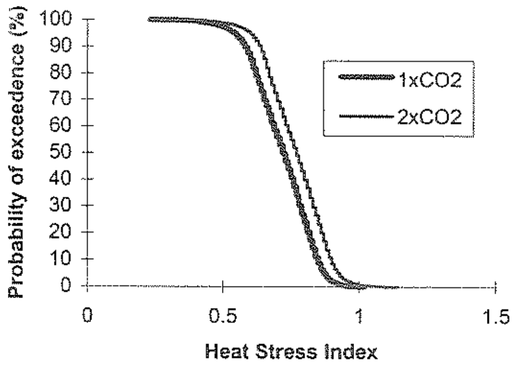

Figure 7 Probabilities of exceedence of the heat stress index under the current climate and with the climate change scenario.

5. DISCUSSION

The model simulates water requirements of Brahman cattle effectively at temperatures at or above 32°C but tends to underpredict them at lower temperatures when compared with measured water needs in controlled environment rooms (Colditz and Kellaway 1972, O'Kelly and Reich 1981). However, total heat loads in such rooms are not necessarily equivalent to those

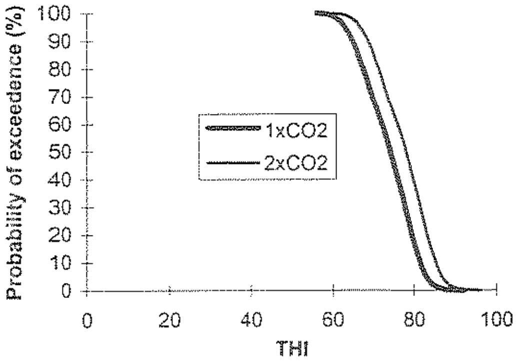

Figure 8 Probabilities of exceedence of the THI under the current climate and with the climate change scenario.

experienced in the field at the same nominal temperature (eg Finch 1983). Finch suggests that the heat exchanges are approximately equivalent in the two environments in the range of 35 to 45°C, suggesting that the model is performing well but that further testing is required at lower temperatures.

Strong linear relationships were found between modelled water requirements and both temperature and THI. In contrast, the relationship between water requirements and the stress index derived from the physically-based model was less robust with factors such as solar radiation, precipitation and vapour pressure adding variability. This suggests that relationships similar to those of King (1983) between water requirements and readily available climate data could be developed for broad scale studies. Similarly, the good correspondence between the stress index using the physically-based model and the empirical THI suggest that studies of heat stress using the more empirical model remain valid. However, the physically-based model used here provides an additional capability to investigate specific situations where the data is available.

The incidence of heat stress as measured by the frequency of days with THI greater than 80 has increased significantly over the 40 year period on record. This is due to both changes in the temperature variables used and also the incidence of drought as drought years appear to be also associated with high stress frequency. The changes experienced over the past 40 years (approximately 60% increase) are proportionately similar to those suggested over the next 100 years in the climate change scenario (138% increase).

Water requirements increased significantly (~13%) under the climate change scenario used here when compared with current conditions suggesting that any overgrazing near watering points is likely to be exacerbated under global change. The smaller median increases in the two indices (5% for THI and 7% for the stress index) disguises the potential significance of the climate change on animal stress. In the current climate, the animal could regulate temperature by sweating alone on all days, with the maximum ratio of evaporative flux density being 0.92. However, under climate change, the value of this index exceeded unity on 92 days in the record suggesting that physiological and behavioral change would be needed by animals to avoid hyperthermia. Similarly, stress as measured by a threshold value of the THI of 80 is currently encountered on only 16% of days and this frequency will more than double (to 38%) under the climate change scenario used here. These results suggest that further selection for cattle lines with effective thermoregulatory control will be needed in the future.

Finch *et al.* (1982) found that thermoregulatory control was negatively correlated with metabolic rate suggesting that it may be difficult to combine the desirable traits of adaptation to high temperture environments with high production potential in cattle although there are possibilities for selection of coat colour and characteristics that may provide some opportunities for selection of heat tolerance (Finch *et al.* 1984). A physically-based model such as that used here could be useful in determining the significance of different sets of thermoregulatory mechanisms for selection programs.

The current work provides a simple assessment of the drinking requirements of cattle in tropical environments. However, some of the assumptions could be improved, for example the parameterisations of metabolic water production and water from feed intake and the inclusion of wind run data is needed to determine the effect this may have. Variations in feed intake and feed quality which occur in the field could be accounted for by linking the model to existing or new models. The hourly weather data could be improved, either by using measured hourly data or using more complicated statistical techniques to downscale variables like rain as at present, the rainfall scheme may lessen the impact of high solar radiation in the middle of the day or the combination of high winds and rainfall at night. Finally, more data on the physiology of tropical animals such as properties of the coat and tissue insulation are needed to allow a full model of tropical cattle to be built.

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