Analysis of heat stress in UK dairy cattle and impact on milk yields

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Abstract
Much as humans suffer from heat-stress during periods of high temperature and humidity, so do dairy cattle. Using a temperature-humidity index (THI), we investigate the effect of past heatwaves in the UK on heat-stress in dairy herds. Daily THI data derived from routine meteorological observations show that during the summer, there has been an average of typically 1 day per year per station over the past 40 years when the THI has exceeded the threshold for the onset of mild heat-stress in dairy cattle. However, during the heatwaves of 2003 and 2006, this threshold was exceeded on typically 5 days on average in the Midlands, south and east of England. Most dairy cattle are in the west and north of the country and so did not experience the severest heat. Milk yield data in the south-west of England show that a few herds experienced decreases in yields during 2003 and 2006. We used the 11-member regional climate model ensemble with the A1B scenario from UKCP09 to investigate the possible future change in days exceeding the THI threshold for the onset of mild heat-stress. The number of days where the THI exceeds this threshold could increase to over 20 days yr⁻¹ in southern parts of England by the end of the century.

Keywords: climate change, heat waves, climate impacts, animal health

1. Introduction

Animals, like humans, suffer in conditions of extreme heat and humidity. For agricultural animals, extreme weather can impair productivity as well impacting animal welfare. The effect on dairy cattle can be relatively easily determined as with twice-daily milking, any drop in yield can be quickly identified, and has an immediate effect on the income generated. We therefore focus on heat-stress in UK dairy herds.

It has been known for over 50 years that dairy cattle are particularly susceptible to heat-stress due to high temperature and humidity (Johnson et al 1963). Measurable physiological consequences include: reduced dry-matter intake, rate of weight gain, fertility of dairy cattle (both sexes) and also milk yield as well as eventual mortality (see e.g. Silanikove 2000, West et al 2003, Jordan 2003, Ravagnolo and Misztal 2000, Boonprong et al 2008, O’Brien et al 2010, Crescio et al 2010 and references therein). These effects reduce the productivity of the herd, with consequences for economic viability (St-Pierre et al 2003). The susceptibility of an individual herd depends on the breed and genetic merit of the herd, with the milk yield of dairy cattle of high genetic merit (usually those selected for high milk yield) being proportionately more affected by heat-stress (e.g. Bryant et al 2007). Some cattle breeds appear to be better acclimatized to warmer temperatures, with some beef cattle adapted to sub-tropical climates better able to withstand prolonged periods of mild heat-stress (Boonprong et al 2008).

In the UK, dairy farming is concentrated in south-west Wales, south-west England, western Midlands and south-west Scotland (figure 1: DEFRA 2008). These hilly, rainy areas are more suited to dairy cattle than to large scale arable farming which dominates the flatter, drier areas in the south and east. Around 90% of dairy cattle are Holstein or Friesian breeds and their crosses. Only about 5% of UK dairy cattle are kept in continuous housing (reared exclusively in barns), but
during the winter most dairy herds are kept indoors (British Society of Animal Science (BSAS)2011). In some areas of the world cattle are kept in barns for longer periods of time, and cooling systems are used to limit heat-stress during the summer (e.g. Smith et al 2012).

A decline of approximately 19% in dairy cattle numbers has been countered by an 18% increase in milk yield per head in the UK between 2001/2002 and 2011/2012, leading to only a 4% decline in total milk production (DairyCo2012). However this increase yield imposes a higher energy burden on the cow. The cows need to dissipate more heat and hence are more susceptible to heat-stress, along with other health problems (West et al 2003, Oltenacu and Broom2010).

In this paper we assess the current occurrence of heat-stress days for dairy cattle and assess the impacts on milk yields. We then investigate potential future impacts on milk yields in a warming world scenario. We outline the temperature-humidity index (THI) used to monitor heat stress and the hourly meteorological data in sections 2 and 3, and present the results in section 4. Milk yield data for herds in the south-west of England are analysed in section 5, along with climate projections in section 6. A discussion of all the results is in section 7.

2. THI

A common measure of heat-stress is THI, developed initially for humans by Thom (1958) and extended to dairy cattle by Berry et al (1964). This combines air temperature and relative humidity: lower temperatures at high humidity give similar heat-stress to higher temperatures at lower humidity. Mader et al (2006) extended the THI to include wind speed and solar radiation, to improve its effectiveness as a proxy for the heat-stress experienced by (beef) cattle. They found that for each $1 \text{ m}^{-1}$ increase in wind speed, the THI can be reduced by 1.99 units, and for each $100 \text{ W m}^{-2}$ decrease in solar radiation, the THI can be reduced by 0.68 units. So Gaughan et al (2008) incorporated wind speed, but not solar radiation, into a heat load index and a related accumulated heat load, obtaining better predictions of animal stress than provided by THI and its time-integral. Solar radiation is a particular concern for dark cattle (Robertshaw 1985, Busby and Loy 1996), and Eigenberg et al (2005) have demonstrated the physiological benefits of shading cattle during summer heat. However solar radiation implicitly influences the basic THI because THI and solar radiation are positively correlated (e.g. Mader et al 2006).

Unlike these studies, our work is not a controlled experiment with dedicated meteorological observations: we use routine data from operational weather stations (section 3). These do not in general include solar radiation, and their wind speeds may be unrepresentative of that experienced by dairy cattle, because wind speeds are more dependent on local topography than are temperature and humidity. So we limit our analysis to the effects of temperature and humidity, assuming moderate sunshine and calm conditions. The THI used in this study is:

\[
\text{THI} = (1.8T + 32) - (0.55 - 0.0055RH) \times (T - 26.8),
\]

(NRC 1971), where $T$ is the temperature in °C and RH is the relative humidity in %. Alternative formulae for THI give similar results (Dikmen and Hansen 2009). Those formulae which place more weight on the humidity work better in humid climates, whereas in drier climates, those which place more weight on the temperature work best (Bohmanova et al 2007). Some authors use daily average temperatures and humidities, others use the maximum temperature and the minimum humidity to calculate the most appropriate THI (Ravagnolo and Misztal 2000). Some studies use a 3 day running mean of THI, which allows the effect of prolonged periods of heat-stress to be captured (West et al 2003, Jordan 2003). The 3 day mean is based on the measurement for the 24 h in question, along with two 24 h periods preceding it. Work by Holter et al (1996) has suggested that the reduction in dry matter intake depends more on the minimum THI experienced by the cow than the maximum THI. This corresponds to work in humans, where night-time temperatures ($T_{\text{min}}$) have a greater impact on mortality and morbidity than day-time temperatures ($T_{\text{max}}$) (e.g. Laaidi et al 2011, Valleron and Boumendil 2004).
A number of studies have correlated THI with physiological measures of cattle stress including the level of panting (Mader et al. 2006), dry-matter intake, and milk temperatures and yield (West et al. 2003) to determine the threshold for the onset of heat-stress. Guidance by the US Government sets thresholds of THI for heat-stress levels (as defined by equation (1)) at 72–78 for mild heat-stress, 78–89 for severe stress and 89–98 for very severe stress. An animal experiencing a THI of 98 or more would not live for very long (Chase 2006). However, the appropriate thresholds will depend on the formulation of the THI. Geographical factors, such as solar radiation intensity, and biological factors such as the different activity levels and breeds of cattle will also affect the thresholds.

There is also evidence for cattle acclimatization. Bryant et al. (2007) found that the onset of the effects of heat-stress in New Zealand cattle occurred at lower THI values than in the USA. The difference in response of humans to the same weather in different parts of the world (e.g. Duncan and Horvath 1988, Nielsen et al. 1993) is well-documented, so acclimatization of cattle is no surprise. Further concerns regarding THI thresholds arise from the continued genetic selection of cattle for milk yield. It is has been suggested that the onset of heat-stress for modern Holstein cattle is at a lower threshold than those in earlier studies, perhaps as low as 65–69 (Bouraoui et al. 2002, Bryant et al. 2007, Zimbelman et al. 2009). In this work, we assume that the response of UK dairy cattle to different THI levels is the same as in the USA. However, further research would need to be done to confirm this assumption, especially given Bryant et al. (2007) results.

Some cattle live mainly in large barns rather than outdoors. A number of studies have investigated the relationship between the THI outside and inside the barn, with a view to developing cooling methods in high temperatures. The difference between temperature and relative humidity inside and outside cattle barns changes with the seasons, and also depends on the barns’ construction (e.g. Seedorf et al. 1998). In general, the temperature is higher indoors (3–5 °C for northern Europe), but the relative humidity varies, depending on the external temperature (Seedorf et al. 1998, Erbez et al. 2010). The resulting effect on THI is therefore complex, but it is on the whole higher indoors than outdoors. In the USA, some barns are equipped with cooling apparatus, including fans and water sprinklers (Morrison et al. 1973). The latter option may be counter-productive, as it does not lower the temperature much, but raises the relative humidity considerably (Smith et al. 2012). Studies have shown that cattle prefer shade to sprinklers when outdoors despite other benefits of sprinklers (e.g. reducing the annoyance by insects, Schütz et al. 2011).

3. The climate data: HadISD

HadISD is a new sub-daily, high-quality dataset created by the Met Office Hadley Centre. It is based on the Integrated Surface Dataset (ISD) held at NOAA’s National Climate Data Centre The current release of HadISD contains just over 6100 stations spread all over the world, with hourly or three-hourly measurements since 1973 of temperature, dewpoint, sea-level pressure, wind speed and direction as well as some cloud data. These data have been quality controlled using an automatic suite of tests designed to be optimal in retaining true natural weather extremes while removing erroneous data. For a full description of the data set construction, see Dunn et al. (2012).

There are 153 HadISD stations in the UK. From these, stations were selected which had no significant gaps and approximately equal numbers of days with >=four observations per day for temperature and dewpoint (spread over at least 12 h) in the seven 5 year periods from 1975–2010. The final station selection is 68 stations spread around the UK (figure 2). For each day with sufficient observation hours with valid temperature and dewpoint measurements, the daily mean temperature and dewpoint were calculated. Station series were checked by eye for inhomogeneities caused by, for example, station moves or instrument changes, but none was found. From these, the mean RH, and subsequently the mean THI for that day were derived. We use a threshold for the onset of heat stress in dairy cattle of THI>70, although
we note that other studies have found that this threshold could be as low as 65 or as high as 75 (Bryant et al 2007).

4. UK THI over 1973 to 2012

The average number of days per year with THI > 70 for each of the 68 stations is shown in figure 2. As expected, the stations in the south and east have more high-THI days than stations in the north and west. The stations in London also show urban warming, but most dairy cattle are away from London and in the west of the country (figure 1), and so experience, on average, 1 or no days with THI > 70 in a year, and are therefore unlikely to suffer regular heat stress in the current climate.

The average number of days per year where the THI > 70 over all the 68 stations in the UK is 0.8. Even at those stations with at least one instance of THI > 70 over the period of record, the average is around 2 days. This is much lower than the number of high-THI days experienced by cattle elsewhere in the world, e.g. USA, Australia and Israel (e.g. West et al 2003, St-Pierre et al 2003, Berman et al 1985). However, in the last decade there have been a couple of high-profile heatwaves in the summers of 2003 and 2006, which affected human health and infrastructure. Therefore it is plausible that these events also had an effect on some UK dairy cattle herds. Segnalini et al (2011) showed that during the summer of 2003 in the Mediterranean basin, some areas usually favourable for animal production were heavily affected by the extreme temperatures. Figure 3 shows the number of days out of the whole year where THI > 70 in 2003 and 2006. In both these years, the number of high-THI days is much greater than the average for the bulk of England shown in figure 2. Wales, and Scotland along with northern and the far south-west of England escaped the worst effects of the heatwaves.

Areas where both high-THI days and high dairy cattle populations (figure 1) coincided during these two years are the north-west Midlands and also the eastern parts of the south-west (Somerset/Avon and surrounding counties). Dairy cattle in the eastern half of England will have suffered more as a result of these heatwaves than their counterparts further west, but the overall impact will have been limited by the lower intensity of dairy farming.

It is likely that most days with THI > 70 occur during the summer, so we now focus on the days in June–July–August (JJA). The heat waves in the summers of 2003 and 2006 were extreme events in their own right (Beniston 2004, Black et al 2004), but over the last few decades, global average temperatures have been rising (IPCC 2007). To investigate the effect that recent climate change has had on the daily summer THI values at each of the stations, distributions combining all the stations were constructed for 1975–1989 and 1995–2009 (two independent 15 year periods), and fitted with a Gaussian, including skew and kurtosis components (figure 4(a)). The standard deviation and skewness did not change much between the two periods. However, the mean and kurtosis have both increased. As the mean remains on the cool side of THI = 60, we conclude that present-day heat-
stress levels in dairy cattle, in terms of milk productivity, are not of immediate concern for most days in the summer. A similar analysis for the running 3 day THI shows very similar mean, skew and kurtosis values to those for the THI (figure 4(b)). The standard deviation is a little smaller, as would be expected for this smoothed version of the index. The change in the distribution has increased the frequency of THIs > 70 by around 20–40% (an increase by 17% (40%) from 0.90 to 1.05 (0.95–1.34) days per JJA averaged over all 68 stations using the data (fitted curve)). However, the extremal values of the THI do not appear to have changed, with a maximum of around 76 for both periods (see inset of figure 4(a)). Using the running 3 day THI, the change in the frequency of days >70 is less clear, with a decrease from 0.73 to 0.68 days using the data, but an increase from 0.51 to 0.87 days using the fitted curve. This uncertainty is unsurprising because the data at these high THI values are noisy.

The heatwave summers of 2003 and 2006 (figure 5) had, on average over the 68 stations, 2.7 and 2.8 days respectively with THI > 70 (2.1 and 3.8 days using the fitted curve). These substantially exceed the 1995–2009 average from the data (1.05 days) or fitted curve (1.34 days). For south-eastern and central England (see figure 3), the average exceeded 5 days with THI > 70 in JJA of 2003 and 2006, whereas for western England and Wales (see figure 3), the average exceeded 3 days.

5. Milk yield and cell count data

Bryant et al (2007) studied the effect of the thermal environment on dairy cattle in New Zealand, finding that milk yield and composition varied nonlinearly with 3 day average THI. The variation depended on the breed and on the genetic merit of animals of the same breed. Thresholds for decreasing milk yield ranged between THI = 65 and THI = 75, with similar ranges for milk composition. West et al (2003) found that the milk yield of dairy cattle in Georgia, USA, fell by 0.69 kg day$^{-1}$ (0.88 kg day$^{-1}$) for each point increase in the concurrent (2 days previous) THI. Ravagnolo et al (2000) found smaller decreases in milk yield of around 0.2 kg per day per point rise in THI. In continental Europe, Renna et al (2010) found measurable changes in the milk yield during 2003 when compared with other, non-heatwave years.

We therefore investigated whether recent weather events in the UK have affected dairy cattle health and milk yields. We obtained data from The Cattle Information Service (www.thecis.co.uk) database which contains information on %...
protein, % butterfat and the number of white blood cells as well as the milk yield (litres per day) for each animal in a herd at approximately monthly intervals. No more detailed information was available after following multiple lines of enquiry. Although this study focuses primarily on the milk yield of the cattle, the cell count may also be a useful indicator of the animal’s health as it correlates with the level of infection. Giesecke (1985) showed that the occurrence of new udder infections and mastitis increased during hot summer months, and so it would be expected that the cell count would rise in dairy cattle that experience heat stress (see also Morse et al 1988).

There are complicating factors in determining whether the change in milk yield is the result of the weather or from physiological factors, such as the number of calves the cow has had (the lactation number or parity) and also how many days since the calf was born (days in milk). These have effects on the milk yield as shown in figure 6.

To avoid the influences of different weather, grazing or feed and routine, we have not pooled data between herds. Each herd has a profile of lactation numbers, but for most herds, there are most measurements from one-calf cows. There is also a sharp drop off in the number of records after around 300 days in milk (DIM). To reduce the impact of these additional factors, we select records for one-calf cows, and split the days in milk into 50 day ranges.

We focus on the August 2003 and July 2006 heatwaves and use data from herds in climatologically warm southern counties with large numbers of dairy cattle (figure 1(c)): Devon, Somerset, Dorset and Wiltshire. The CIS records have 123, 40, 28, and 23 unique herd IDs for these four counties. Milk yields and other measures were recorded approximately monthly, the exact date depending on the herd. The peak temperatures in the two heat waves were on 10 August 2003 and 19 July 2006 respectively. We selected herds with values recorded within 1 day of these peaks (9–11 August 2003 and 18–20 July 2006) to sample the strongest effect of the heat. This gave a sub-sample of 17 herds. To protect anonymity, the precise locations of the herds are not given by CIS, so we could not specifically select herds from low-lying land inland sites, which are likely to have been hottest.

We would expect heat stress to lead to a fall in the milk yield during the two events, possibly alongside an increase in white blood-cell count. But only four herds show any indication of a decrease in milk yields during the summers of 2003 and 2006. We illustrate the impacts for two of these herds. For one-calf cows and bins of 0–50, 50–100, and 100–150 DIM, figure 7 shows that the yield for herd 198 is dominated by a seasonal cycle, with minima in late summer/autumn in each year, slightly accentuated in 2003 and 2006 but also in the cool year 2009. The regular minima could be the result of seasonal dependence of the quality of grazing (see e.g. New Zealand Pasture Growth Index at http://www.nzxagri.com/article/89.html).

Herd 4199 (figure 8) shows a sharp decline in the milk yield for all DIM ranges coinciding with the 2006 heatwave. The yield drops from around 30 litres per cow per day to between 15–201. Dairy cattle with 0–100 DIM also had low yields in June, whereas those with 100–150 DIM had lower yields in September. There is no evident effect of the 2003 heatwave, but the curve is noisy because there are few data in 2003, as shown by the very low cattle numbers. There is an increase in the cell count values in July 2006 (note logarithmic scale) from around 80–100 to >300: the high values in winter 2003 are noisy and unreliable owing to paucity of data. The mean cell counts for August 2006 fall in the 98th percentile for all means, and below the third percentile for milk yields. To highlight 2006 we have superposed all years in figure 9. The 0–50 DIM yield measurements, corresponding to the blue curve in figure 8, of 2006 in mid June and mid July are the lowest yields in the entire series.

These two herds, 198 and 4199, have the strongest decrease in milk yield associated with the heatwaves of 2003 and 2006. Most herds showed no detectable impact. The
monthly measurement interval may have masked the impacts as the persistence of any effect of heat stress appears to be low. In combination with the smallness of the THI > 70 sample, this has made detection of systematic impacts difficult, and as outlined in section 4, on average there are few days in the UK where cattle would experience heat stress.

6. Climate projections

To study the effect of any future change in the climate on the number of days with high THI we use the climate projections made for the UK Climate Predication ’09 assessment (UKCP09, Murphy et al. 2009). An 11-member perturbed-physics ensemble of regional climate model (RCM) runs is available for the UK at 25 km × 25 km resolution on a rotated pole grid. The RCM was driven by (global model used to specify boundary conditions), and takes into account the various factors that influence the climate over the UK, both natural (e.g. volcanic eruptions, variations in solar output) and anthropogenic (e.g. greenhouse gas and aerosol emissions and land use changes), and their likely change under a given scenario when calculating the future climate. The change in anthropogenic emissions is given by the A1B medium emissions scenario (also known as representative climate pathways). The emissions in the A1B scenario are the result of a world with rapid economic growth and a rapid spread of new technologies, but with a drop in population in the last 50 years of the period and a convergent income way of life between regions. There is a balanced emphasis on all energy sources; fossil, and non-fossil. Other scenarios exist which have higher or lower levels of anthropogenic emissions, but these are not available in the 11-member UKCP09 ensemble.

The projections include daily temperature and relative humidity for a 150 year run, from 1950–2099. We have combined grid elements together into seven regions (South East, South West, East Anglia, Wales, Midlands, Northern England and Scotland: figure 10).

For each region, we calculate the number of days each grid box is above the THI threshold. We then calculate the average number of days across the region, for each year and for each ensemble member, resulting in 11 THI-curves for each region. We show these for the south-west region in figure 11, and for the remaining six regions, in figure 12 in the appendix.

As can be seen in figure 11, within a single ensemble there is a high inter-annual variability, but across all ensemble members, there is a steady rise in the number of days per year where a grid box has a THI > 70. In the south-west of the UK,
There are on average 2.65 days yr$^{-1}$ where the THI $>$ 70 between 1950 and 2000, with little trend. This corresponds well with the observed amount of between 1 and 2 days on average (figure 2). After around 2030, there is an accelerating increase in the median number of days with THI $>$ 70 which by the end of the century reach around 30 days yr$^{-1}$. The high inter-annual variability indicates that individual years can have many more—or fewer—than the ensemble median number of days exceeding the threshold.

The seven different regions cover the mainland of Britain and there is a clear latitude dependence on the number of days that exceed the THI threshold. Under this A1B scenario, Scotland and Northern England are projected to have very few days where the THI exceeds the threshold, even by the end of the century. In Wales, the Midlands and East Anglia the ensemble mean reaches between 20 and 30 days yr$^{-1}$ by 2099, and in the south-east of England, over 40 days yr$^{-1}$ could be reached.

Most dairy cattle in the UK are in the west of the country (figure 1), in south-west and northern England, the Midlands, Wales and Scotland (figure 10). Of these, the south-west and Midlands appear to be most susceptible to having a large number of days where dairy cattle could be suffering from heat-stress by the end of the century. However the severity is likely to be higher for the few dairy cattle kept in the south-east.

Studies in Hungary (Solymosi et al 2010) and South Africa (Nesamvuni et al 2012) show similar results, with increasing levels of heat stress in dairy cattle expected over time. Using different emissions scenarios, Nesamvuni et al (2012) unsurprisingly found that severe stress would be more common under maximum daily climate conditions in South Africa. Solymosi et al (2010) found that the number of heat stress days increased in all from 1961–1990 to 2021–2050, using a number of different GCMs for the same emissions scenario (A1B for all but one model which was A2). However the amount of increase varied from model to model, and the baseline value also had a large range between models. Seven out of the nine models showed an increase in the number of heat-stress days by a factor of four over at least 80% of the
Figure 12. Regional projections of THI as in figure 1 but for Scotland, Northern England, Wales, East Anglia, the English Midlands and South-East England. South-West England can be found in figure 11.
country (for 2021–2050). This is similar in magnitude to the change expected in the southern regions of England and Wales (see figures 11 and 12).

7. Discussion

Currently the climate of the UK results in few days during an average year when the THI rises above the threshold for the onset of heat-stress in dairy cattle. Also, the distribution of dairy cattle farming in the UK is such that there are comparatively few dairy farms in the south-east which is most susceptible to high THI days in the summer. However there are some indications that during the heatwave event of 2006 at least one herd in the south-west of England did have decreased milk yields of around 30%. RCM projections of the future change in the number of days exceeding the THI threshold for the onset of heat stress indicate that for southern parts of the UK this could increase from on average 1–2 per year to over 20 per year by 2100, with correspondingly more during heatwave events.

In the USA, the projected continued gain in milk yield per head is expected to offset milk production lost due to heat-stress in future warmer summers, and similar could be expected for the UK. However, the reduction in milk yield may be as high as 0.9 kg of milk production per cow per day for each percentage point the THI lies above the heat-stress threshold (West et al. 2003), though other studies find a reduction of 0.2 kg day\(^{-1}\) (Ravagnolo et al. 2000). At present, south-west England, south Wales and the Midlands are the regions with high densities of dairy cattle which are most at risk from any rise in the number of days with high THI, as they are closest to the areas which have already experienced substantial numbers of high THI days during heat waves. The cost of a reduction in milk yield or running cooling mechanisms to improve the herd’s welfare could have a large impact on the livelihood of the farmers in these regions. Moreover, if a short-term, high THI period is part of a longer weather trend, then there can be compounded problems, especially if drought and hot periods affect the supply and quality of feed (Bryant et al. 2007). The changes observed in the milk yields for the UK herds studied here could be the result of drought associated with the hot weather reducing the pasture quality as well as effects from heat stress in the animals.

Furthermore, it is important that further research is invested in setting an exact threshold or indeed another UK-tailored measure related to THI, indicating the onset of bovine heat-stress, since the projection of the direct impact on dairy cattle farming varies so much between location and breed, and evidence-based decisions are required. Future dairy farms may become more intensive where cattle are predominantly kept indoors (POST-NOTE 2012). Heat-stress in these environments may be more of an issue in the summer, but in these cases regulating the temperature with cooling systems is practical, albeit expensive. The difference in the temperature and humidity between the interior of barns and the outside has been studied, both in closed and open-sided structures (Seedorf et al. 1998, Erbez et al. 2010). Temperatures were always higher inside barns, as was the THI, but humidity offsets varied (Erbez et al. 2010). Therefore it is possible, in future heatwave events, permanently barned cattle may suffer more heat-stress than those which graze outside depending on the cooling systems installed. Heat-stress affects all animals, not just dairy cattle, and so the potential impact of any future investigations of this nature is large.

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References

Beniston M 2004 The 2003 heat wave in Europe: a shape of things to come? An analysis based on Swiss climatological data and model simulations Geophys. Res. Lett. 31 L02202

Berman A, Folman Y, Kaim M, Mamen M, Herz Z, Wolfenson D, Arieli A and Graber Y 1985 Upper critical temperatures and forced ventilation effects for high-yielding dairy cows in a subtropical climate J. Dairy Sci. 68 1488–95

Berry J L, Shanklin M D and Johnson H D 1964 Dairy shelter design based on milk production decline as affected by temperature and humidity Trans. Am. Soc. Ag. Eng. 7 329–31

Black E, Blackburn M, Harrison G, Hoskins B and Methven J 2004 Factors contributing to the summer 2003 European heatwave Weather 59 217–23

Bohmanova J, Misztal I and Cole J B 2007 Temperature-humidity indices as indicators of milk production losses due to heat stress J. Dairy Sci. 90 1947–56

Boonprong S, Choosetha A, Sribhen C, Parvizi N and Vajrabukka C 2008 Productivity of Thai Brahman and Simmental-Brahman crossbred (Kabinburi) cattle in central Thailand Int. J. Biometeorol. 52 409–15

Bouraoui R, Lahmar M, Majdoub A, Dijemali M and Belyea R 2002 The relationship of temperature-humidity index with milk production of dairy cows in a Mediterranean climate Anim. Res. 51 479–91

Bryant J R, Lópe¿z-Villalobos N, Pryce J E, Holmes C W and Johnson D L 2007 Quantifying the effect of thermal environment on production traits in three breeds of dairy cattle in New Zealand N. Z. J. Agric. Res. 50 327–38

British Society of Animal Science (BSAS) 2011 Continuous housing of dairy cows http://bsas.org.uk/animal_briefs/continuous-housing-of-dairy-cows-2.pdf (accessed January 2014)

Busby D and Loy D 1997 Heat stress in feedlot cattle: producer survey results Beef Research Report, 1996 paper 26

Chase L E 2006 Climate change impacts on dairy cattle Climate Change and Agriculture: Promoting Practical and Profitable Responses pp 111–17–23
Dunn R J H, Willett K M, Thorne P W, Woolley E V, Durre I, Eigenberg R A, Brown-Brandl T M, Nienaber J A and Hahn G. L. Climate Change 2007: The Physical Science Basis. IPCC 2007

Duncan M T and Horvath S M 1988 Physiological adaptations to thermal stress in tropical Asians Eur. J. Appl. Physiol. 57 540–4

Dunn R J H, Willett K M, Thorne P W, Woolley E V, Durre I, Dai A, Parker D E and Vose R S 2012 HadISD: a quality controlled global synoptic report database for selected variables at long-term stations from 1973–2010 Clim. Past Discuss 8 1763–833

Eigenberg R A, Brown-Brandl T M, Nienaber A J and Hahn G. L 2005 Dynamic response indicators of heat stress in shaded and non-shaded feedlot cattle, Part 2: predictive relationships Biosyst. Eng. 91 111–8

Erbez M, Falta D and Chládek G 2010 The relationship between temperature and humidity outside and inside the permanently open-sided cows’ barn Acta Universitatis Agriculturae et Silviculturiae Mendelianae Brunensis (Brno, Česká Republika), LVIII 91–6

Gaughan J B, Mader T L, Holt S M and Lisle A 2008 A new heat load index for feedlot cattle J. Anim. Sci. 86 226–34

Giescke H W 1985 The effect of stress on udder health of dairy cows Onderstepoort J. Vet. Res. 52 175–93

Holter J B, West J W, McGilliard M L and Pell A N 1996 Predicting ad libitum dry matter intake and yields of Jersey cows J. Dairy Sci. 79 912–21

IPCC 2007 Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change ed S Solomon, D Qin, M Manning, Z Chen, M Marquis, K B Averyt, M Tignor and H L Miller (Cambridge: Cambridge University Press) pp 650

Johnson H D, Ragsdale A C, Berry I L and Shanklin M D 1963 Environmental physiology and shelter engineering, with special reference to domestic animals: LXVI. temperature-humidity effects including influence of acclimation in feed and water consumption of Holstein cattle Univ. Missouri Agri. Exp. Sta. Res. Bull. 66 43–83

Jordan E R 2003 Effects of heat stress on reproduction J. Dairy Sci. 86 E104–14

Laaidi K, Zeghnoun A, Dousse B, Briend P, Vandentorren S, Giraudet E and Pascal B 2011 The impact of heat on islands on mortality in Paris during the august 2003 heat wave Environ. Health Perspect. 119 254–9

Mader T L, Davis M S and Brown-Brandl T 2006 Environmental factors influencing heat-stress in feedlot cattle J. Anim. Sci. 84 712–9

Morrisson S R, Givens R L and Lofgreen G P 1973 Sprinkling cattle for relief from heat stress J. Anim. Sci. 36 428–31

Morse D, De Lorenzo M A, Wilcox C J, Collier R J, Natzke R P and Bray D R 1988 Climatic effects on occurrence of clinical mastitis J. Dairy Sci. 71 848–53

Murphy J M et al 2009 UK Climate Projections Science Report: Climate Change Projections Met Office Hadley Centre, Exeter, UK

Nesamvuni E, Lekalakala R, Norris D and Ngambi J W 2012 Effects of climate change on dairy cattle, South Africa Afr. J. Agric. Res. 7 3867–72

Nielsen B, Hales J R S, Strange S, Christensen N J, Warberg J and Saltin B 1993 Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment J. Physiol. 460 467–85

NRC 1971 A Guide to Environmental Research on Animals (Washington, DC: National Academy Science)

O’Brien M D, Rhoads R P, Sanders S R, Duff G C and Baumgard L H 2010 Metabolic adaptations to heat stress in growing cattle Domest. Anim. Endocrinol. 38 86–94

Olteanu P A and Broome D M 2010 The impact of genetic selection for increased milk yield on the welfare of dairy cows Anim. Welfare 19 39–49

Perry M and Hollis D 2005 The generation of monthly gridred datasets for a range of climatic variables over the UK Int. J. Climatol. 25 1041–54

POST-NOTE 2012 UK Parliament Briefing Papers Number 404 “Livestock Super Farms” www.parliament.uk/briefing-papers/POST-PN-404.pdf (accessed October 2012)

Ravagnolo O, Miszal I and Hoogenboom G 2000 Genetic component of heat stress in dairy cattle, development of heat index function J. Dairy Sci. 83 2120–5

Ravagnolo O and Miszal I 2000 Genetic component of heat stress in dairy cattle, parameter estimation J. Dairy Sci. 83 2126–30

Renna M, Lussiana C, Malfaito V, Mimossi A and Battaglini L M 2010 Effect of exposure to heat stress conditions on milk yield and quality of dairy cows grazing on Alpine pasture 9th European IFSA Symp. (Vienna, 4–7 July 2010) pp 1338–48

Robertshaw D 1985 Heat loss of cattle Stress Physiology in Livestock Vol I: Basic Principles ed M K Yousef (Boca Raton, FL: CRC Press) pp 55–66

Schütz K E, Rogers A R, Cox N R, Webster J R and Tucker C B 2011 Dairy cattle prefer shade over sprinklers: effects on behavior and physiology J. Dairy Sci. 94 273–83

Seedorff J et al 1998 Temperature and moisture conditions in livestock buildings in Northern Europe J. Agric. Eng. Res. 70 49–57

Segalini M, Nardone A, Bernabucci U, Vitali A, Ronchi B and Lactera N 2011 Dynamics of the temperature-humidity index in the Mediterranean basin Int. J. Biometeorol. 55 253–63

Silanikove N 2000 Effects of heat-stress on the welfare of extensively managed domestic ruminants Livest. Prod. Sci. 67 1–18

Smith J F, Collier R J, Harner J P III and Bradford B J 2012 Strategies to reduce heat stress in dairy cattle Proc. 27th Annual Southwest Nutrition and Management Conf. http://animal.cals.arizona.edu/swmnc/Proceedings/2012.pdf pp 65–84

Solymosi N, Toma C, Kern A, Marót-Agóts A, Barcza Z, Kőnyves L, Berke O and Reiczigel J 2010 Changing climate in Hungary and trends in the annual number of heat stress days Int. j. Biometeorol. 54 423–31

St-Pierre N R, Cobanov B and Schmitkey G 2003 Economic losses from heat stress by US livestock industries J. Dairy Sci. 86 152–77

Thom E C 1958 Cooling degree days Air Cond., Heat. Vent. 55 65–9

Valleron A J and Boumendil A 2004 Épidémiologie et canicules: analyses de la vague de chaleur 2003 en France [epidemiology and heat waves: analysis of the 2003 episode in France] C. R. Biol. 327 1125–41

van der Marel P and Franx M 1993 A new method for the identification of non-Gaussian line profiles in elliptical galaxies Astron. J. 107 725–39

West J W, Mullinix B G and Bernard J K 2003 Effects of hot, humid weather on milk temperature, dry matter intake, and milk yield of lactating dairy cows J. Dairy Sci. 86 232–42

Zimbelman R B, Rhoads R P, Rhoads M L, Baumgard L H and Collier R J 2009 A re-evaluation of the impact of temperature humidity index (THI) and black globe humidity index (BGHI) on milk production in high producing dairy cows Proc. 24th Annual Southwest Nutrition and Management Conf. http://animal.cals.arizona.edu/swmnc/Proceedings/2009/ProceedingsList_09.html