Impact of global climate change on the health, welfare and productivity of intensively housed livestock

Tadeusz Kuczynski[1], Victoria Blanes-Vidal[2], Baoming Li[3],
Richard S. Gates[4], Irenilza de Alencar Nääs[5], Daniella J. Moura[5],
Daniel Berckmans[6], Thomas M. Banhazi[7]

(1. *Department of Environmental Engineering, University of Zielona Gora, Z. Szafrana 1, Zielona Gora Poland*;
2. *Faculty of Engineering. University of Southern Denmark, Niels Bohrs Alle 1*, 5230, *Odense, Denmark*;
3. *Department of Agricultural Structure and Bioenvironmental Engineering, China Agricultural University, Beijing* 100083, *China*;
4. *Agricultural and Biological Engineering*, 1304 *West Pennsylvania Ave, University of Illinois at Urbana-Champaign, Urbana IL* 61801, *USA*;
5. *Agricultural Engineering College, State University of Campinas, Campinas, São Paulo, Brazil*;
6. *M3-BIORES, Katholieke Universiteit Leuven, Kasteelpark Arenberg* 30, *Leuven Belgium*;
7. *National Centre for Engineering in Agriculture, University of Southern Queensland, West St, Toowoomba, QLD* 4350 , *Australia*)

Abstract: Major scientific studies have shown that global warming (i.e. increasing average temperature of the Earth) is now a reality. The aims of this paper are to broadly review the underlining causes of global warming, the general effects of global warming on social and environmental systems and the specific effects of resulting from global warming phenomena severe fluctuations in weather patterns, particularly heat waves on livestock health, welfare and productivity. Finally this article aims to summarise some common sense climate control methods and more importantly to highlight the required future research and development (R&D) work that is necessary to achieve a new level of building environment control capability, and thus ensure that the intensive livestock industries will be able to cope with the changed external climate. With the increasing temperatures on a global scale, the most direct effect of the high temperature on the animals is heat stress, which has been proven to have a variety of negative effects on animal health, welfare and productivity. Different potential measures could be taken in future to alleviate the increased heat stress. Some of these measures are mere adaptations or improvements of current engineering solutions. However, facing the complex challenges of global warming and particularly resulting from it the rapid increase of the number of consecutive days with significantly higher than average temperatures will probably require novel solutions, including new designs based on solid engineering judgment, development of new engineering standards and codes to guide designs, the exploration of new and superior building materials, the need for better energy management, and the development of substantially more “intelligent” control systems that will balance changing exterior disturbances, interior building loads and demands to the biological needs of the occupants of the structures.

Keywords: livestock, global climate change, greenhouse effect, animal welfare, heat stress, temperature, , cooling, agricultural buildings
DOI: 10.3965/j.issn.1934-6344.2011.02.0-0

Citation: Kuczynski, T., Blanes-Vidal, V., Li, B M., Gates, R. S., Nääs, I. A., Moura, D. J., Berckmans, D. and Banhazi, T. M. Impact of global climate change on the health, welfare and productivity of intensively housed livestock. Int J Agric & Biol Eng, 2011; 4(2): —.

1 Introduction

Temperature is one of the most important environmental variables that can affect the health, welfare, and the production efficiency of domesticated animals. Over the past few decades, numerous long-term climate changes (i.e. changes in regional climate characteristics, including temperature, humidity, rainfall, wind, and severe weather events) have been observed, due to global warming (i.e. an overall warming of the planet, based on average temperature over the surface). Global warming

---

Received date: 2010-12-10 **Accepted date:** 2011-05-16

Corresponding author: Thomas M. Banhazi, Ph.D, Professor. Email: thomas.banhazi@squ.edu.au.

significantly affects weather on both global and local scales. Some weather phenomena have become increasingly frequent and intense. Extreme heat waves become more frequent and more severe, which particularly affects the climate in buildings. The 2003 heat wave in Europe caused a 20%–30% increase in average July temperature. In many European countries extremely hot temperatures lasted over 20 consecutive days. The 2009 south-eastern Australia heat wave is considered probably the most extreme in the region's history. In 50 separate locations the records for consecutive, highest daytime and overnight temperatures were recorded, in some locations reaching 12 consecutive days with temperatures over 40℃.

The events with unusually high temperatures lasting for long periods of time seem to affect particularly the regions which have never before experienced such situation, i.e. moderate climate regions[1].

In these regions, livestock buildings are usually designed with particular emphasis on periods of cold and moderate temperatures. Extended time of extremely hot weather can significantly worsen animal welfare, decrease animal productivity and increase mortality. The new situation should significantly affect thermal design of livestock buildings; their construction, temperature control systems, housing systems which could enable the animals to adjust to prolonged periods of heat stress. Taking into account that long periods of heat waves in summer are often followed by severe winter, one should also remember that livestock buildings should be able to maintain proper indoor climate all year around.

The main aim of this article is to review the issues related to global warming, mostly understood here as prolonging time of extremely high temperatures in summer and its potential affect on welfare, health and productivity of animals kept in agricultural buildings and farm workers attending those animals. The specific aims of this review paper are to broadly review the underlining causes of global warming, the general effects of global warming on social and environmental systems, and the specific effects of heat waves on livestock health, welfare and productivity. Finally this article aims to summarise some common sense climate control methods and more importantly to highlight the required future research and development (R&D) work that is necessary to achieve a new level of building environment control capability, and thus to ensure that the intensive livestock industries will be able to cope with the changed external climate.

2 Definition of global warming and brief review of underlying causes

Earth receives its energy from the Sun which radiates energy at very short wavelengths, predominately in the visible or near-visible (e.g., ultraviolet) part of the spectrum. Approximately one-third of Earth's incident solar energy is reflected and back-scattered within the atmosphere and never reaches the surface. The remaining solar energy is absorbed mostly by the Earth's surface and, to a lesser extent, by the atmosphere. To balance the absorbed incoming energy, the Earth must, on average, radiate the same amount of energy back to space. Because the Earth is much colder than the Sun, it radiates energy at much longer wavelengths, primarily in the infrared part of the spectrum. Much of this thermal radiation emitted by the land and ocean is absorbed by the atmosphere, including clouds and water vapor, and reradiates back to Earth[2]. By an analogy to the physical processes which take place in a typical greenhouse, this is called the greenhouse effect.

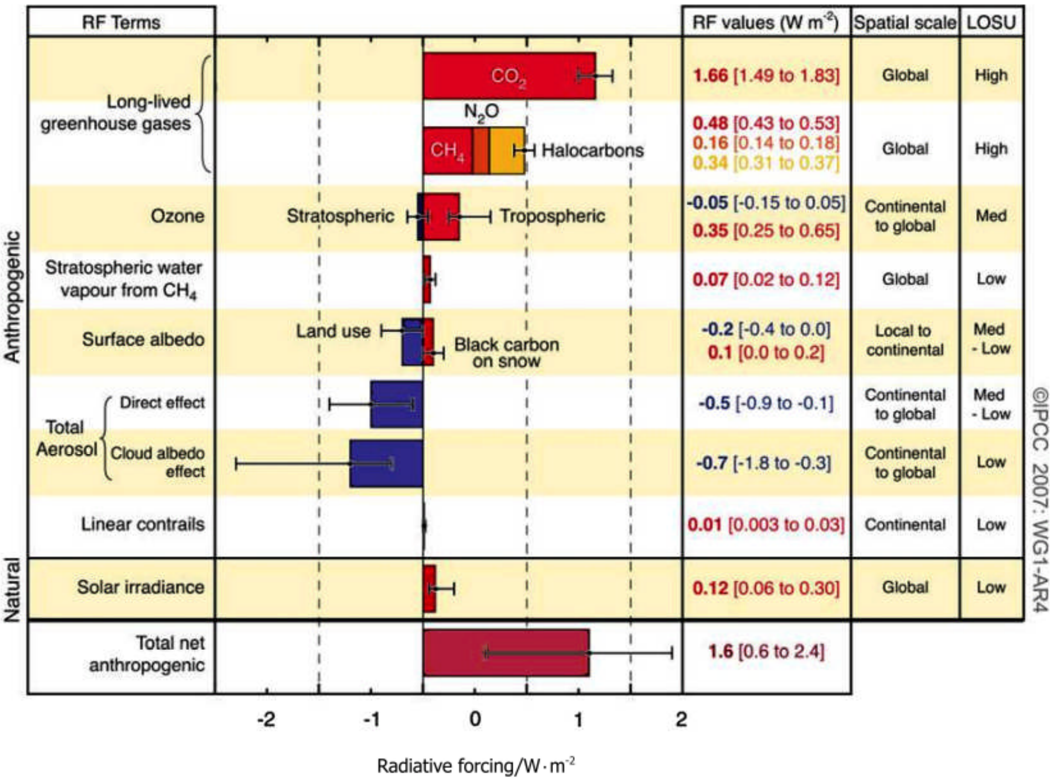
The energy absorbed eventually by the Earth's surface and atmosphere is estimated as approximately 240 W/m^2. The radiation emitted by the Earth to space would correspond to an annual global mean temperature of about -19℃[3]. This "expected" annual global mean temperature is much colder than the actual annual global mean temperature of approximately 14℃[4]. The surplus energy (difference between the expected and measured global mean surface temperatures) is absorbed by the Earth's surface and the atmosphere[3].

Earth's surface temperature has been kept at relatively stable level for thousands of years because relatively stable concentrations of greenhouse gases (GHG) including water vapor, carbon dioxide (CO_2), and methane (CH_4), the most important GHG, were maintained in the Earth's atmosphere. Other GHG that could affect the Earth's surface temperature are nitrous oxide (N_2O), halocarbons and tropospheric ozone precursors. Increasing the GHG production rates intensifies the greenhouse effect, trapping additional energy and thus warming Earth's climate. Its importance dramatically increased commencing from the start of the industrial era, when human consumption of fossil fuels elevated CO_2 levels from a concentration of approximately (280 ppm_v, 1 ppm=1 μL/L) 250 years ago to more than (379 ppm_v) today.

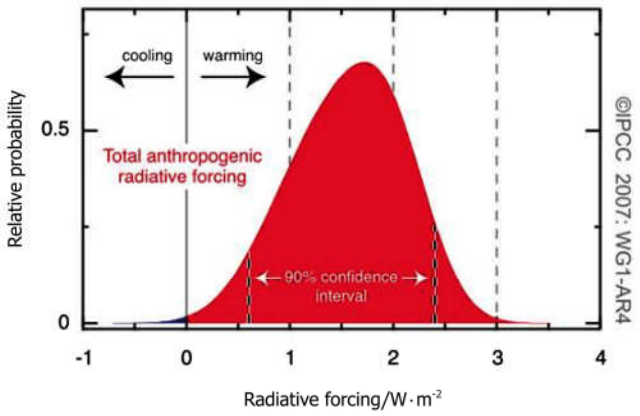
The amount of warming depends on various feedback mechanisms. For example, as the atmosphere warms, its concentration of water vapor increases, providing a positive feedback loop for further intensifying the greenhouse effect. This in turn entails more warming, which causes an additional increase in water vapor, in a self-reinforcing cycle. This water vapor positive feedback may be strong enough to approximately double the increase in the greenhouse effect due to the added CO_2 alone[2].

The influence of a factor that can cause climate change, such as a GHG, is often evaluated in terms of its radiative forcing (RF), which is a measure of how the energy balance of the Earth-atmosphere system is influenced when factors that affect climate are altered[2]. A positive RF suggests a net imbalance that will warm the surface. Recent estimates of global mean RF and their 90% confidence intervals in 2005 for various agents and mechanisms are shown in Figure 1[2]. The combined RF due to increases in CO_2, CH_4, N_2O and halocarbons is +2.6 W/m^2, and its rate of increase during the industrial era is significant[3]. The CO_2 RF increased by 20% from 1995 to 2005, which is the largest change for any decade in the last 200 years. Similar trends in RF are seen for CH_4 and N_2O.

Some natural phenomena also affect the RF. Changes in solar irradiance, for example, increased the average RF by about +0.12 W/m^2 over the period 1 750 – 2 005[2]. Clouds behave similarly to the GHG. However, this effect is offset by cloud reflectivity, such that on average, clouds tend to have a cooling effect on climate at a RF level of approximately -0.5 W/m^2[3]. Total net anhropogenic increase RF in the period 1 750 – 2 005 is roughly estimated to be 1.6 W/m^2[2].



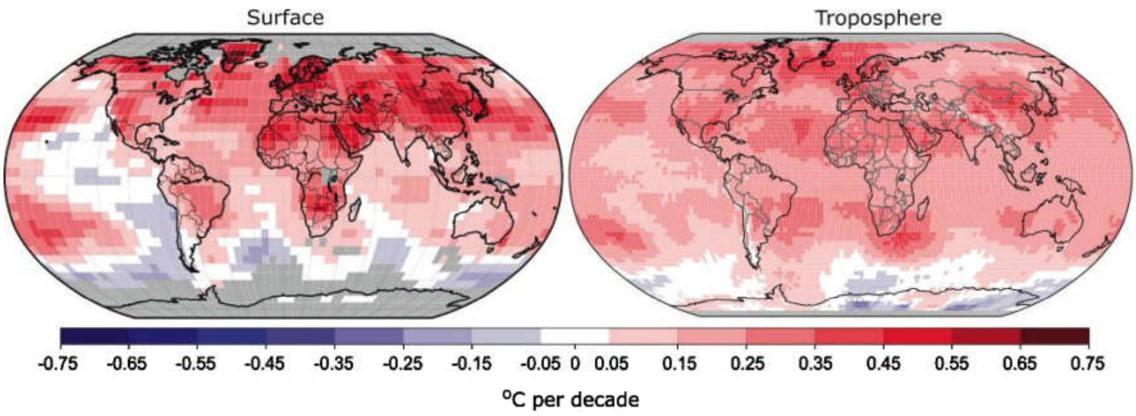
a



b

Figure 1 (a) Global mean radiative forcings (RF) and their 90% confidence intervals in 2005 for various agents and mechanisms. Columns on the right-hand side specify the best estimates and confidence intervals (RF values); typical geographical extent of the forcing (spatial scale); and level of scientific understanding (LOSU) indicating the scientific confidence level. Errors for CH_4, N_2O and halocarbons have been combined. The net anthropogenic RF and its range are also shown. The best estimates and uncertainty ranges can not be obtained by direct addition of individual terms due to the asymmetric uncertainty ranges for some factors; the values given here were obtained from a Monte Carlo technique. Additional forcing factors not included here are considered to have a very low LOSU. Volcanic aerosols contribute an additional form of natural forcing but are not included due to their episodic nature. The range for linear contrails does not include other possible effects of aviation on cloudiness. (b) Probability distribution of the global mean combined RF from all anthropogenic agents shown in (a). The distribution is calculated by combining the best estimates and uncertainties of each component. The skew in the distribution is created by the negative forcing terms, which have larger uncertainties than the positive terms[2].

Figure 2 illustrates the global temperature rate of change, measured in ℃ per decade. Changes in Earth's surface and the troposphere temperature are distributed unevenly. In some parts of Europe, Asia, Africa, and North America, Earth's surface temperature increase in the years 1979–2005 reached as high as 0.4–0.6℃ per decade, considerably exceeding the average value of 0.18℃ per decade recorded over the last 25 years. Eleven of the last twelve years (1995-2006) ranked among the twelve warmest years in the instrumental record of global surface temperature (since 1850)[5]. For the same reason, including the first five years of the 2000's, the 100-year linear trend (1906-2005) increased 0.14℃ decade^{-1} over the corresponding (1901-2000) trend of 0.6℃ decade^{-1} to 0.74℃ decade[5,6].



a

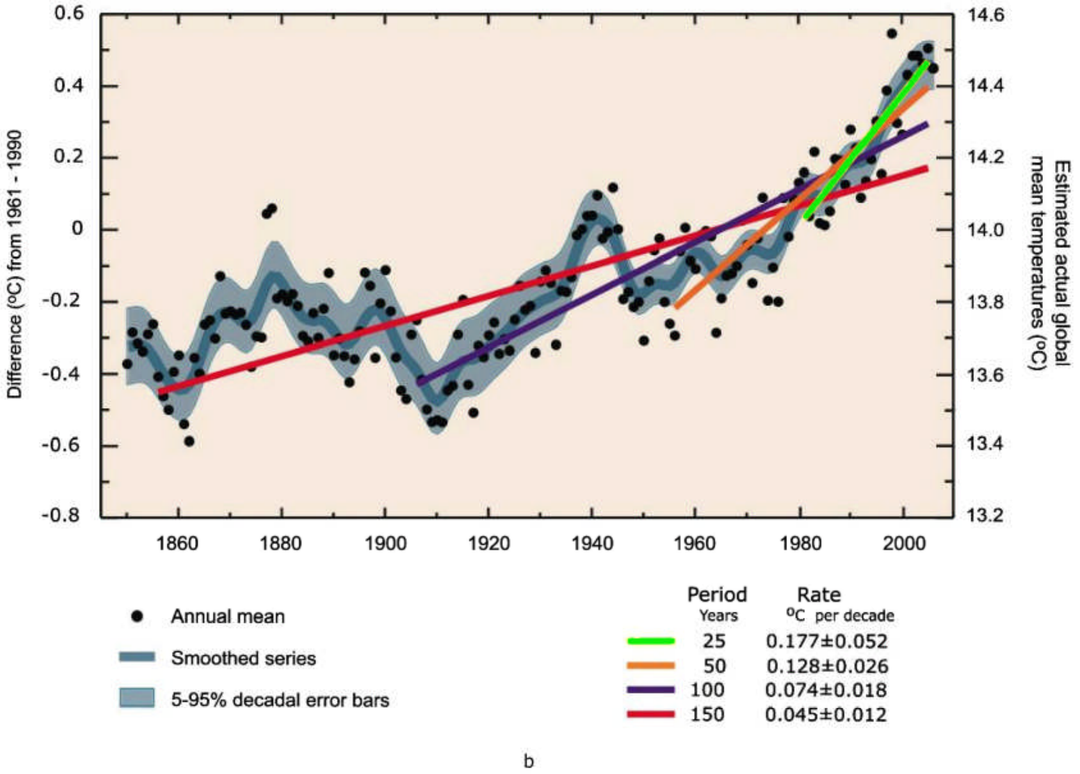


Figure 2 (a) Patterns of linear global temperature trends over the period 1979 to 2005 estimated at the surface (left), and for the troposphere from satellite records (right). Grey indicates areas with incomplete data. (b) Annual global mean temperatures (black dots) with linear fits to the data. The left hand axis shows temperature anomalies relative to the 1961 to 1990 average and the right hand axis shows estimated actual temperatures, both in ℃. Linear trends are shown for the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red). The smooth blue curve shows decadal values, with the decadal 90% error range shown as a pale blue band about that line. The total temperature increase from the period 1850 to 1899 to the period 2001 to 2005 was 0.76℃ ± 0.19℃[2].

3 Brief review of the potential effects of global warming on the environment

A key element of anticipated global climate change is in the significant changes in weather events on a local scale. Weather phenomena are expected to change in frequency and intensity. These phenomena include heat waves, which are unusually hot weather conditions, occurring for an extended period of time of days or weeks, and characterized by air temperatures substantially higher than the average temperature registered for that time of year, in that specific region. Other phenomena include heavy rainfall events, floods, droughts, tropical storms and hurricanes. It is predicted that with global warming there will be an increase in the frequency and magnitude of these so-called “extreme climate events” that also include floods, unusual temperatures and bush-fires[6], and shifts in weather patterns with some typically wet regions seeing even greater rainfall, and some dry regions become even drier. Extreme climate events are responsible for significant material losses in the world. In many countries (including the USA and Europe) extreme heat has had a negative influence on the agricultural productivity[7]. Recent predictions suggest a high probability (above 90%) that by 2090 much of Earth’s arable lands will see summer temperatures that exceed the hottest on record to date[8] – with severe consequences for agricultural productivity.

Many natural systems seem to be already affected by global warming. The consistency between observed and modeled changes in several studies and the spatial agreement between significant regional warming and consistent impacts at the global scale is sufficient to conclude with high confidence that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems[9].

Global warming can be tied to such events as the retreat of glaciers, reduction of the area of the Arctic sea ice, melting of ice cover and as a consequence, rising sea levels[2,6,9]. It is highly likely that events such as the enlargement and increased numbers of glacial lakes, increasing ground instability in permafrost regions and rock avalanches in mountain regions will be more frequent. In addition, changes in some Arctic and Antarctic ecosystems, earlier spring peak discharge in many glacier- and snow-fed rivers, warming of lakes and rivers in many regions can also be expected[9].

On the basis of satellite observations since the early 1980s, there is high confidence that there has been a trend in many regions towards earlier ‘greening’ of vegetation in the spring linked to longer thermal growing seasons due to recent warming[9]. There is also very high confidence, based on more evidence from a wider range of species, that recent warming is strongly affecting terrestrial biological systems, including changes such as: earlier timing of spring events leaf-unfolding, bird migration and egg-laying), poleward and upward shifts in ranges in plant and animal species[9].

Changes in marine and freshwater biological systems have been observed[9], including changes in algal, plankton and fish abundance in high-latitude oceans, increases in algal and zooplankton abundance in high-altitude lakes and range changes of fish populations in rivers. These changes are often associated with rising water temperatures and with related changes in salinity, oxygen levels and circulation of water bodies. Global warming might also affect some aspects of human health, such as heat-related mortality in Europe, the spread of infectious disease vectors in some areas[10], and allergenic pollen production in Northern Hemisphere[9].

It should be mentioned that the impact of climate change to date has not been evenly distributed among various geographical regions in the world, and this trend is expected to accelerate. Developing countries tend to be more vulnerable to climate change events than developed countries, due to the vulnerability of their economies and the direct costs of some means of adaptation. Thus climate change could ultimately exacerbate income inequalities between and within countries resulting in social instability[6]. Figure 3[10] illustrates the direction and magnitude of change of selected health impacts of global warming.

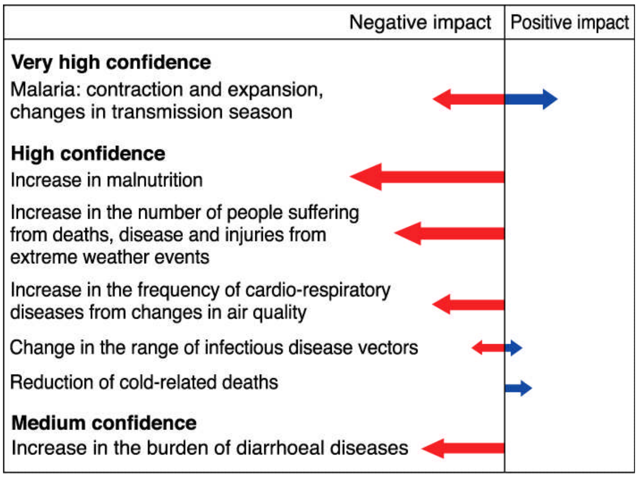


Figure 3 Direction and magnitude of change of selected health impacts of climate change[10].

4 Extent of change – best & worst scenarios

The potential consequences of climate change have been described in the previous section. These effects are complex and thus difficult to predict as they depend on scientific, economic and social factors as well as on their interactions. The main objective of a number of current research projects is the evaluation of the consequences of predicted climate change on different aspects on the environment and human life. These studies base their estimations on the current predictions of GHG emissions and temperature rise reported in the literature that will determine the extent of the consequences.

The assessment of climate change requires a global perspective and a very long time horizon that covers periods of at least a century. As the exact knowledge of future anthropogenic GHG emissions is impossible, emissions scenarios become a major tool for the analysis of potential long-range developments. According to IPCC[2], scenarios are a plausible and often simplified description of how the future may develop, based on a coherent set of assumptions about driving forces and key relationships. Scenarios are images of the future, or alternative futures. They are neither predictions nor forecasts. Rather, each scenario is one alternative image of how the future might unfold. Emissions scenarios are a central component of any assessment of climate change.

Scenarios facilitate the assessment of future developments in complex systems that are either inherently unpredictable, or have high scientific uncertainties.

Scenarios that have a similar demographic, social, economic and technological storyline are grouped in the same Family Scenario. Four scenario families comprise the Special Report on Emission Scenarios (SRES) and are designated as scenarios A1, A2, B1 and B2. The SRES scenarios are based on different storylines. The storylines are narrative descriptions of a scenario (or family of scenarios), highlighting the main scenario characteristics, relationships between key driving forces and the dynamics of their evolution. Storylines of the four family scenarios are summarized below. A more detailed description of the storylines of all SPES scenarios can be found in SRES[11].

The A1 scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system.

The three A1 groups are distinguished by their technological emphasis: fossil-intensive (A1FI), non-fossil energy sources (A1T) or a balance across all sources (A1B), in which “balance” is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end use technologies.

The A2 scenario family describes a very heterogeneous world. The underlying theme is self reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than other storylines.

The B1 scenario family describes a convergent world with the same global population as in the A1 storyline (i.e. that peaks in mid-century and declines thereafter), but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability, including improved equity, but without additional climate initiatives.

The B2 scenario family describes a world in which the emphasis is on local solutions to economic, social and environmental sustainability. It is a world with continuously increasing global population (at a rate lower than A2), intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.

The temperature and sea level rises projected for each SRES-based projections are summarized in Table 1[5].

Table 1 Projected global average surface warming and sea level rise at the end of the 21st century under six different scenarios[5]

Scenario	Mean Temperature Increase/℃		Sea level rise/cm
	Best estimate	Likely range	Likely range
B1	1.8	1.1 – 2.9	18 - 38
A1T	2.4	1.4 – 3.8	20 – 45
B2	2.4	1.4 – 3.8	20 – 43
A1B	2.8	1.7 – 4.4	21 – 48
A2	3.4	2.0 – 5.4	23 – 51
A1FI	4	2.4 – 6.4	26 – 59

The large difference between predictions of the different scenarios indicates the complexity involved in making such predictions and the large amount of uncertainty inherent in climate change models. Despite this variation, a few general conclusions can be drawn from the IPCC report[5].

1) For the next two decades, a warming of about 0.2℃ per decade is projected for a range of SRES emission scenarios.

2) Even if activities having an impact on the balance between energy entering and exiting the planetary system

were reduced and held constant at year 2000 levels, a further warming trend would occur over the next two decades at a rate of about 0.1℃ per decade, due mainly to the slow dynamic response of the oceans.

3) Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.

Regarding the geographical distribution of the climate change, projected warming in the 21st century shows scenario independent geographical patterns similar to those observed over the past several decades. Warming is expected to be greatest over land and at most high northern latitudes, and least over the Southern Ocean and parts of the North Atlantic Ocean.

Finally, we should take into account that due to the complexity of the problem, other well documented studies present different results regarding temperature rise predictions. For example, according to Stainforth et al.,[12], a doubling of carbon-dioxide levels (worst scenario) could eventually lead to an increase in worldwide temperature of anything between 1.9℃ and 11.5℃, a far greater level of uncertainty than the 2-5℃ rise predicted by the Intergovernmental Panel on Climate Change.

In relation to the predicted global temperature rise in this century we can expect numerous environmental impacts which may seriously influence many areas of human life in the future. Some of them are illustrated in Figure 4[9].

5 Direct effects of increasing temperatures on livestock production

Climate affects animal production in several ways, among which the most important are[13-16]: the impact of changes in livestock feed-grain availability and price; impacts on livestock pastures and forage crop production and quality; changes in livestock diseases and pests; and the direct effects of weather and extreme events on animal health, growth and reproduction. Other effects of climate driven changes in animal performance arise mainly from change in their diet[17,18]. The impact of climate change on pastures and rangelands may include deterioration of pasture quality, and poor quality of subtropical grasses in temperate regions as a result of warmer temperatures and less frost; however, there could also be potential increase in yield if climate change may turn into favorable as a result of increase in CO_2[19,20] assuming sufficient water availability.

With increasing average global temperature, the most direct effect on animals is clearly that of heat stress[21]. Heat stress is a term used by the thermal physiologists to mean an excessive demand on the animal for heat dissipation under high ambient temperature[22], and can be expressed by a number of indices. Black globe-humidity index (combining the solar radiation, ambient temperature, wind speed, and the relative humidity), effective temperature (ET, combining the ambient temperature and solar radiation), temperature-humidity index (THI, combining the ambient temperature and the relative humidity) and temperature-humidity-velocity index (THVI, combining the temperature, relative humidity and air velocity over the animals), have been regarded as good indicators of stressful thermal conditions. These bioenergetics parameters and other various systems approaches for implementation are thoroughly reviewed in a recent review article[23]. Nissim[22] suggested that the best physiological parameter to objectively monitor animal welfare in hot environment was to monitor core temperature.

In summer of 2006 (from the start of May to the end of September), a national survey of the health and welfare of pigs under intensive rearing conditions was made in China. Ten pig farms from different regions were chosen, and field measurements including the housing system, environmental indices, such as ambient temperature, relative humidity, wind speed, THI, the ambient CO_2, NH_3, H_2S concentration, behavioral records were analyzed and data about performance and the mortality were collected. The relevant results showed that: during July – September period, the hottest season in most parts of China, the average Temperature-Humidity Index (THI, as defined by Nissim[22]) the value of pig breeder houses was usually over 80. According to

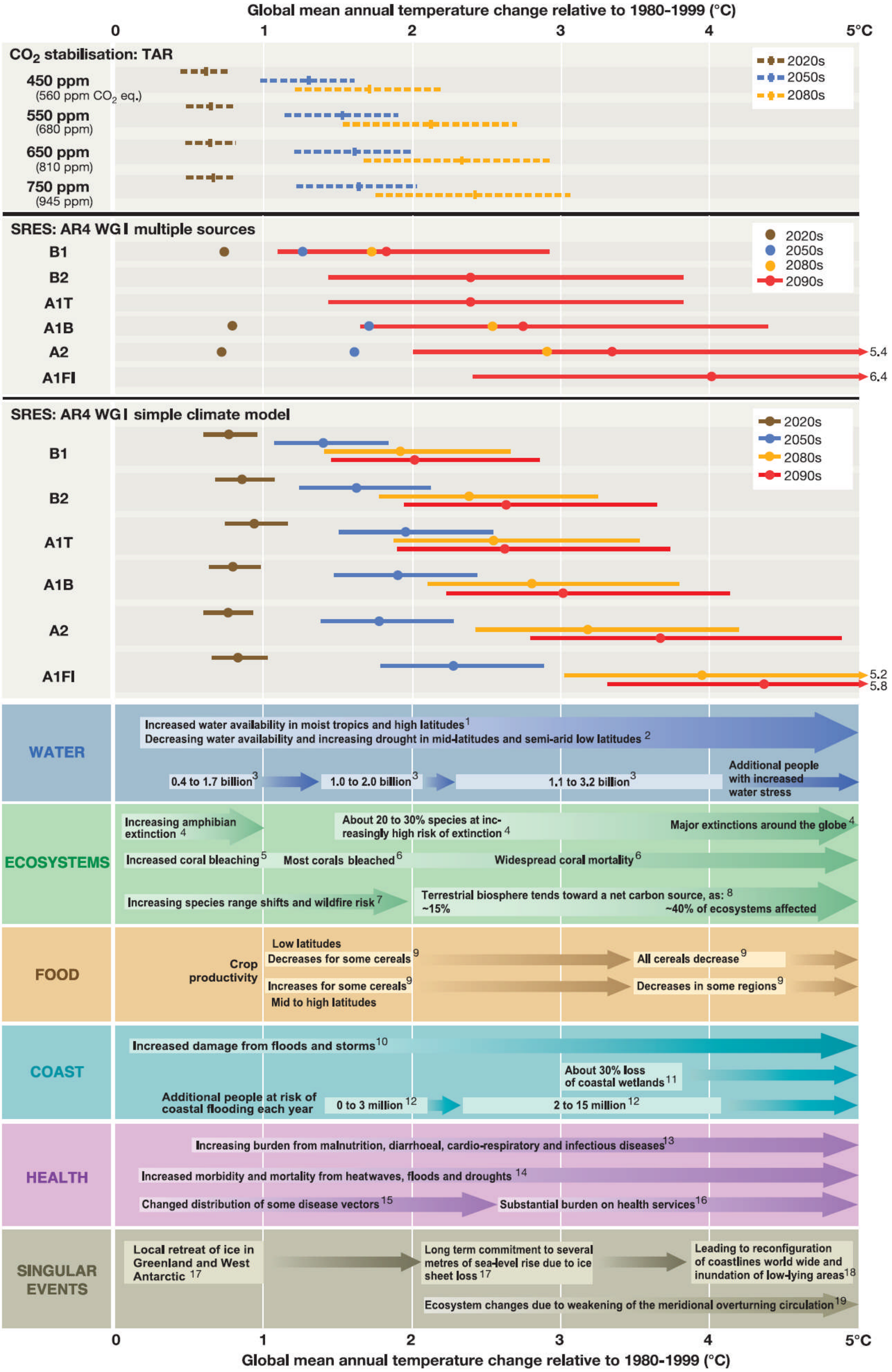

Global mean annual temperature change relative to 1980-1999 (°C)
0
1
2
3
4
5°C
CO2 stabilisation: TAR
450 ppm
(560 ppm CO2 eq.)
550 ppm
(680 ppm)
650 ppm
(810 ppm)
750 ppm
(945 ppm)
2020s
2050s
2080s
SRES: AR4 WG I multiple sources
B1
B2
A1T
A1B
A2
A1FI
2020s
2050s
2080s
2090s
5.4
6.4
SRES: AR4 WG I simple climate model
B1
B2
A1T
A1B
A2
A1FI
2020s
2050s
2080s
2090s
5.2
5.8
WATER
Increased water availability in moist tropics and high latitudes 1
Decreasing water availability and increasing drought in mid-latitudes and semi-arid low latitudes 2
0.4 to 1.7 billion 3
1.0 to 2.0 billion 3
1.1 to 3.2 billion 3
Additional people with increased water stress
ECOSYSTEMS
Increasing amphibian extinction 4
About 20 to 30% species at increasingly high risk of extinction 4
Major extinctions around the globe 4
Increased coral bleaching 5
Most corals bleached 6
Widespread coral mortality 6
Increasing species range shifts and wildfire risk 7
Terrestrial biosphere tends toward a net carbon source, as: 8
~15%
~40% of ecosystems affected
FOOD
Crop productivity
Low latitudes
Decreases for some cereals 9
All cereals decrease 9
Increases for some cereals 9
Decreases in some regions 9
Mid to high latitudes
COAST
Increased damage from floods and storms 10
About 30% loss of coastal wetlands 11
Additional people at risk of coastal flooding each year
0 to 3 million 12
2 to 15 million 12
HEALTH
Increasing burden from malnutrition, diarrhoeal, cardio-respiratory and infectious diseases 13
Increased morbidity and mortality from heatwaves, floods and droughts 14
Changed distribution of some disease vectors 15
Substantial burden on health services 16
SINGULAR EVENTS
Local retreat of ice in Greenland and West Antarctic 17
Long term commitment to several metres of sea-level rise due to ice sheet loss 17
Leading to reconfiguration of coastlines world wide and inundation of low-lying areas 18
Ecosystem changes due to weakening of the meridional overturning circulation 19
0
1
2
3
4
5°C
Global mean annual temperature change relative to 1980-1999 (°C)

Figure 4 Examples of global impacts projected for changes in climate (and sea level and atmospheric CO_2 where relevant) associated with different amounts of increase in global average surface temperature in the 21st century. This is a selection of some estimates currently available. All entries are from published studies in the chapters of the Assessment. Edges of boxes and placing of text indicate the range of temperature change to which the impacts relate. Arrows between boxes indicate increasing levels of impacts between estimations. Other arrows indicate trends in impacts. All entries for water stress and flooding represent the additional impacts of climate change relative to the conditions projected across the range of SRES scenarios A1FI, A2, B1 and B2. Adaptation to climate change is not included in these estimations. For extinctions, 'major' means ~40% to ~70% of assessed species. The table also shows global temperature changes for selected time periods, relative to 1980-1999, projected for SRES and stabilisation scenarios. To express the temperature change relative to 1850-1899, add 0.5℃. Estimates are for the 2020s, 2050s and 2080s, (the time periods used by the IPCC Data Distribution Centre and therefore in many impact studies) and for the 2090s. SRES-based projections are shown using two different approaches. Middle panel: projections from the WGI AR4 SPM based on multiple sources. Best estimates are based on AOGCMs (coloured dots). Uncertainty ranges, available only for the 2090s, are based on models, observational constraints and expert judgement. Lower panel: best estimates and uncertainty ranges based on a simple climate model (SCM), also from WGI AR4. Upper panel: best estimates and uncertainty ranges for four CO2-stabilisation scenarios using an SCM. Results are from the TAR because comparable projections for the 21st century are not available in the AR4. However, estimates of equilibrium warming are reported in the WGI AR4 for CO_2-equivalent stabilisation. Note that equilibrium temperatures would not be reached until decades or centuries after greenhouse gas stabilisation[10].

Nissim[22], THI values of 70 or less are considered comfortable, 75–78 stressful, and values greater than 78 induce extreme distress and animals are unable to maintain thermoregulatory mechanisms, thereby facing a severe stressful thermal condition. Under global climate change with longer duration heat spells and more extreme temperatures, it is expected that the condition will become more severe for the animals. The responses of pigs to heat stress is panting and raised body temperature; high level of hormones (such as cortisol) concentration; less locomotion and more lying behaviors; less feed intake and reduced body weight; etc., which may affect the health and welfare of animals. Greater incidence of leg diseases may be one of the results. An experimental cooling cover for sows was recently developed[24]. Collins and Weiner[25] proposed that heat stress itself could directly and adversely affect the health of the dairy cow, and Niwano et al. [26] reported that the incidence of health problems in livestock increased during warm summer months.

Heat stress has a variety of detrimental effects on livestock[27]. Recently, a U.S. working group of researchers completed a five year (2001-2006) multi-state research project on the impact of heat stress on animals[28]. The justification for this group, and its follow-up[28], can be explained in simple economic terms: "Environmental and management stressors erode efficiency and cost livestock production enterprises billions of dollars annually in lost potential profitability. For example, summer heat stress results in annual losses to the dairy industry that total $5-6 billion, due to reduced milk production and productive potential"[28]. The summer 2003 heat wave in Europe generated losses of approximately €42 million in the poultry production industry alone[29]. In France 4 million broilers died representing a 15% loss in productivity. In Spain there was a mortality of 15% to 20% while productivity decreased 25% to 30%. In the USA St-Pierre et al. [30] estimated economical losses of livestock varied from $120 to $900 million for broiler, pig, beef cattle and dairy cows respectively. These losses occurred by performance reduction including reduced growth rates, reduced feed intake, poor milk and egg production, increases in mortality and reproductive losses. In 1977 more than 700 dairy cows died during a heat wave in California[31]. In both 1992 and 1999 in Nebraska, and in 1995 in Iowa and Nebraska, heat waves led to $20 million losses in livestock production[7]. While strict economics are one metric for assessing the impact of global climate change, the resultant and associated stresses on people, communities and the poultry and livestock welfare cannot be neglected.

A key research focus of some W-173 and W-1173 members included novel means of monitoring physiological responses to stressors. These so-called bioinstrumentation systems were developed and employed to achieve new means for monitoring core body temperature in livestock. Telemetry-based systems for measuring core body temperature in livestock and poultry were developed[32,33], as well as technologies for body temperature measurements in beef cattle[34,35], dairy cattle[36-38], horses[39-42] and poultry[43], using various tympanic, vaginal, venal, ruminal (bovine), gut (equine, porcine and poultry) and rectal (equine, poultry) temperature probe modifications to characterize and standardize body temperature measures within and among species. Body surface temperature response to environment was quantified using infrared thermography[44-46], and a special calorimeter device for accurate measurement of heat transfer[47] and evaporation[48] from cow hides was developed.

A retrospective analysis of historical heat wave events, coupled with an evaluation of modeling approaches resulted in specific means for improving management to reduce the acute impacts of heat waves and chronic heat stress in beef cattle on feedlots[49]. Models were developed to relate cow thermoregulatory responses, feed intake patterns and interactions associated with cattle genetics, hide color and hair coat thickness, to production performance characteristics[50-54].

Cattle response to heat stressors including temperature, humidity, wind speed, and solar radiation were incorporated into an algorithm to predict respiration rate[43,55,56]. Respiration rate was found to be an excellent indicator of heat stress, and the developed model provides a means to identify at-risk individuals. Heat stress also affects fertility in pasture-bred beef cows; for example if average ambient temperatures exceed 2C above normal a 7% reduction in pregnancy rates in Bos taurus cattle were found[57,58].

Heat stress impacts on dairy cattle have been addressed by participants of W173. Studies conducted included novel fan-sprinkler configurations for free stall cooling[59], effectiveness of commercial fan/mist systems[60-62], effect of solar radiation load as a contributor to heat stress[48], the effects of management practices on heat load and heat dissipation (such as growth hormone use and calf vaccination programs[63,64], and variability associated with genomic differences among tissues (skin, mammary cell cultures, white blood cells, liver, ovarian follicles and muscle) of dairy cattle exposed to thermoneutral and heat stress conditions[65-67]. These results can be used to identify individual cattle that are resistant or sensitive to thermal stress, and the genomic analyses provided insight into the time-course of tissue responses to thermal stress.

Thermal stress was characterized in both pullets and layers and its influence was evaluated on birds before, during and after molting. Such results are particularly important to determine building supplemental heat and ventilation requirements for layer houses[68,69] and under new management systems[70]. A novel means of bird cooling that involved partial surface wetting to relieve heat stress was demonstrated, and its use in the development of a thermal discomfort index for laying hens subjected to acute thermal stress was conducted[71-73]. Studies to characterize feeding behavior of laying hens were conducted to better quantify bird welfare[74-77]. The effect of variable water temperature for laying hens during heat stress was evaluated[75], with a clear preference by birds to water near thermo-neutral temperatures rather than colder. Substantial progress was also made on updating heat and moisture production data for poultry[78-81] and swine[82], and understanding the relation between stocking density under both thermonuetral and heat-stress conditions[70,81]. Recent trends for heavier broilers exacerbate heat stress effects[83,84].

Transportation stress in livestock can occur as a result of handling, animal crowding, trailer temperature, ventilation and air velocity and the duration of travel. Researchers have studied these factors by modeling trailer designs and monitoring physiological responses during transport in accordance with guidelines currently established or proposed for the transportation of livestock. Strategies have been evaluated to minimize effects of transport stress on cattle[85,86] and horses[41,42,87]. A unique approach is the modeling of air circulation patterns in transport trailers[41]. These studies suggest that horse trailer designs need to be improved for current climate conditions[41,42,88]. Stress associated with beef cattle shipping includes increased susceptibility to respiratory tract and other infectious diseases[89], with excessive morbidity and mortality rates encountered despite vaccination against respiratory diseases.

Heat stress has significant effects on milk production and reproduction in dairy cows[90-92]. Extreme events such as heat waves, may particularly affect beef cattle and dairy production[93]. Estimations were done for cows producing 15, 20 and 25 kg milk/day, and the conclusions were that under the global change scenario milk production might decline[94]. Lima et al.[95] studied the heat wave profile for the São Paulo State in Brazil and found that the cows adaptation to the hot environment might play an important role during the occurrence of heat waves, and often the calculation of the decline in milk yield was overestimated to the animals that were adapted.

Poultry are particularly vulnerable to heat stress conditions. Birds have no possibility to lose heat by sweating, thus losses by convection and respiration remain the only mechanisms for taking the heat out of them. There is general consensus among scientists and growers on optimum ambient temperature range for well feathered 4-6 week old broilers. The differences which sometimes happen are connected with the fact that temperature sensed by animals (often called an “effective temperature”) depends not only on temperature of the air but also on all other factors which affect heat exchange between animal and its direct surroundings – air temperature, humidity and velocity[96], type of the flooring material[97], its wetness or radiant heat exchange between animals and building walls and ceiling. Regarding the effect of temperature, humidity and air velocity on heat stress of market size broilers, Tao and Xin[98] developed a temperature–humidity–velocity index (THVI) to delineate the synergistic effects of the thermal components on the birds, based on the core body temperature rise after 90 min exposures to the thermal conditions.

Another group of factors which affect effective temperature is connected with animals themselves as well as the way of their housing and management. The most important issues here seem to be: animal age, their health status, appetite, energy input in feed[99] or diurnal activity[100]. Sex, genotype, as well as goal of selection appeared to affect relation between temperature, weight gains, feed efficiency protein and fat deposition[101,102]. There is a continuous genetic selection in broilers in order to get the best production results and meat quality. Unfortunately, improvements in production results are usually associated with narrowing birds’ thermo neutral zone and increasing their vulnerability to heat stress[102].

Some research data on effect of temperature on weight gains of Ross x Ross male broilers in week 4, 5 and 6, given by May et al. [103], are presented in Figure 5. As can be seen there was no clear trend for weight gains in week 4. For week 5 and particularly week 6 however there was a dramatic reduction in weekly gains when the air temperature was raised above approximately 21℃.

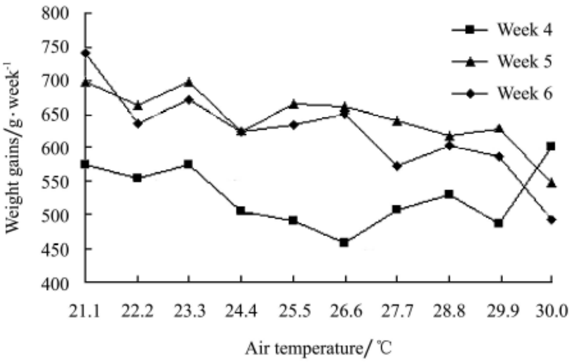


Figure 5 Effect of air temperature on weight gains of Ross × Ross male broilers (May et al. 1998)

The effects of heat stress are accentuated when the minimum daily temperatures are high. The animals will not cool down and may suffer more from the heat discomfort, forming the basis for so-called time integrated variable control systems[104]. The data presented in Figure 5 were obtained by using 10 scenarios of keeping temperatures at a constant level for the period of week 4 to week 6 for the temperature range 21.1℃ to 31.1℃. Actually the temperatures rarely used to remain at very high level for very long, although at present the number of consecutive days with high temperature significantly grows up. Probably to more accurately model the real thermal conditions, Knight et al.[105] assumed that a few days periods of high temperatures were followed by the periods of normal temperature.

6 Heat stress mitigation options

Potential countermeasures to alleviate heat stress and improve the animal welfare are briefly discussed in this section.

For ranging animals or animal rearing in the houses with outdoor access, shade shelter is suggested to ameliorate the heat stress in the summer. Silanikove and Gutman[106] reported that the non-shaded cows experienced much greater strain than the shaded cows. Nissim[22] suggested that the provision of shade shelter is essential to the welfare of farm animals in areas where typical ambient temperature during summer exceeds 24℃ and THI exceeds 70.

No matter what kind of livestock, and what kind of rearing system, sufficient drinking water is the most important factor for the animal's health and welfare[107], with watering location being equally important. This can be problematic if regional water shortages occur as part of climate change. In addition, nutritional imbalance and deficiencies may exacerbate the effects of heat stress[108], so it is necessary to provide the animals with nutritionally balanced diet.

Due to the high cooling efficiency, evaporative cooling systems (evaporative cooling pads, or low- or high-pressure misting with or without fans) are widely used in greenhouses and livestock production operations in regions with hot and dry climates worldwide, and they are also useful for the decrease of the heat stress[109-111]. When the outdoor climate is hot and humid, the efficacy of evaporative cooling systems greatly decreases. However, the economic benefits of these systems have been shown to be positive even in climates considered rather humid[112-118]. As a result, indoor air temperatures rise above the recommended levels, and humidity becomes high [119-122], which can exacerbate heat stress. It has been shown that any evaporative cooling strategy which follows a line of constant or reduced enthalpy can reduce temperature humidity index in the facility[120,121] and result in the optimal of possible environmental conditions. However, under these conditions, air velocity strongly affects convective animal heat losses and plays an important role in thermal comfort[123] which explains the popularity of sprinkler/fan systems and so-called tunnel ventilation systems with evaporative cooling. These systems must have good quality water to be effective, which may become a challenge under long-term draughts.

The effect of the air velocity around animals (specifically, in chickens), on different production factors (such as, broiler performance, feed and water consumption, growth and water balance), and the ability of increased air velocity to avoid animals stress under hot conditions have been studied in the literature[72,98,103,124-127]. According to Yahav et al., [125], air velocity at birds' level should range from 1.5 m/s to 2m/s, when air temperature is 35℃.

Rate of ventilation, together with some other factors, such as building geometry, location, number and size of the inlets and exhaust fans and the presence of indoor obstacles, determines the airflow pattern in the poultry buildings and, therefore, air velocity in the zone occupied by the animals[123,128]. Negative pressure conventional cross-ventilation may be not appropriate for poultry farms located in hot, humid climates, as it may not provide high and uniform air velocities at the level of the broiler chickens which is necessary to relieve bird heat stress [123,128,129]. The system most commonly used for increasing air velocities building for broilers is tunnel ventilation in which the exhaust fans are placed at one end of the building and air inlets at the opposite end. The air is supposed to move with air velocity at a level of approximately 2 m/s through all the length of a building, thus cooling the birds by convection (provided that air temperature does not exceed an upper limit near bird core body temperature). The main problem is the very long distance for a fresh ventilation air to move from air inlet to exhaust fans. Incoming air on its way through building is being heated and humidified by the sensible and latent heat produced by the birds[119-121] as well as getting polluted by toxic gases. This favors the birds which are closest to air inlets or sprinkler lines compared to those remaining on exhaust ventilation side. Still, even at air velocity of 1.85 m/s in building 120 m long, the temperature difference between its front and rear side may exceed 3℃[130]. As one of the most serious problems connected with tunnel ventilation Czarick and Tyson[130] mention broilers migration toward the air inlet, which leads to overcrowding at the front side of the house. To protect against this kind of birds migration air deflectors which increase local air velocity are suggested[130] as well as migration fences which physically prevent birds to move at larger distances[131].

An alternative solution is to utilize horizontal or vertical mixing fans, suspended below the ridge or from the ceiling, which create circular or elliptical areas of high air velocity at bird level. The air speed increases from about 0.5-1.0 m/s directly below the center of the fan, reaches its maximum of 1.5-2.0 m/s at about 3 m from the center and then slowly goes down to 0.5-0.9 m/s at 8 m from the fan center[132]. Such velocity profiles (from 0.5-2.0 m/s at a radius of 8 m) encourage broilers to seek the thermal conditions which would best suit their needs, as found by Bottcher et al. [132]. At indoor temperature 25℃, 0.5 kg broilers initially avoided the circular area directly under fan where air speeds were the highest. After only five minutes, most of these empty areas had been filled by birds, suggesting that some of birds preferred lower effective temperature directly under fan and managed to get there. In contrast to bird migration characteristic for tunnel ventilation this kind of migration takes place at very limited area with relatively broad spectrum of thermal conditions and because of that should not lead to overcrowding.

Still, another technical possibility of increasing air velocities is the design of separate air inlets for cold and hot weather. Cold weather air inlets might be high speed ceiling or wall inlets directing the incoming air parallel to the ceiling surface whereas hot weather air inlets are to direct the incoming ventilation air to floor level[133].

Other methods for reducing heat stress are possible for pigs and cattle. Shi et al. [134] used a floor cooling system as an approach to provide a comfortable sleeping area for the pig in hot weather. The pig's lying behavior was greatly affected by the floor temperature. More than 85% of the pigs were lying in the sleeping area when the floor temperature was below 26℃, while only 10% - 20% of the pigs were lying in the sleeping area when the floor temperature was about 30℃, and hardly any when the floor temperature was above 33℃. When using the floor cooling system, the floor temperature of the sleeping area was controlled at 22-26℃, even though the air temperature was as high as 34℃, which improved the comfort of the pigs in the sleeping area, and improved the welfare of the pigs. Cummins[135] used different bedding materials (wood shavings, sand, ground limestone, shredded paper and rubber mats) for dairy cows, and found that the cows had higher preference for ground limestone which had the lowest temperature of 25.9℃ at 25 mm below the surface, and might facilitate cooling of the animals, and reduce the heat stress. Dong et al. [136] compared three cooling system for relieving farrowing/lactating sows of heat stress under the warm and humid production climate in southern China, and found out that the tunnel ventilation with drip cooling system provided the most cost-effective cooling scheme. More recently, an experimental cooled cover for gestating sows has been shown to be successful in reducing sow heat stress[24].

7 Research requirements and engineering solutions

Controlled environment agriculture was invented and implemented as the opportunities for improved productivity exceeded the added costs for energy and (sometimes) labor. More animals or plants can be managed in a uniform way to produce a superior product as compared to production in unprotected environments. While global climate change is anticipated to create widespread impacts on food, fiber and energy production, it is the shifts from current conditions and the increased variability and incidence of extreme that perhaps pose the greatest challenges to the engineering community. If global climate change meant that a region was faced only with a change in its current climate pattern, to something different but similarly variable, then our current engineering solutions would be readily adaptable. While this is in itself not trivial, it is conceivable that agricultural and biological engineering training will continue to incorporate an appreciation of the global nature of agricultural production, and hence facilitate a more international approach to adapting engineering designs from other regions and cultures. In a sense, this is a natural progression of the way that modern agriculture has been adopted.

However, it is the nature of the predicted global climate changes (ref. Figure 4) that necessitate a study of the research questions we should be asking, and the sorts of engineering solutions that we will be asked to provide. These changes are not simple shifts to a warmer mean temperature, but rather will include higher incidence of severe events (tornadoes, hurricanes, extreme rain events, extreme wind events) and new climate challenges including drought, floods and seasonal weather pattern disruptions, to regions. Addressing this class of environmental challenge will require substantially more effort than the mere adoption of existing technologies to new locales; it will require novel new designs based on solid engineering judgment, development and adoption of new engineering standards and codes to guide designs, the exploration of new and superior building materials in the face of a changing global supply of conventional construction materials, the need for better energy management with higher efficiency of use to counteract the anticipated greater need for environment control, and the development of substantially more "intelligent" control systems that will balance changing exterior disturbances, interior building loads and demands to the biological needs of the occupants of the structures.

Finally, superior environment control systems are needed which allow individual animals or plants to find or achieve their unique optimal conditions within a range of "good" conditions[23]. This sort of control system is vastly more complicated than current thermostat-drive mechanical ventilating, heating and cooling systems. A reliance on new forms of information acquisition (e.g. biosensors) coupled with vastly improved systems analysis and integrative synthesis tools will be critical for such systems to profitably achieve better performance than the status quo designs.

Clearly, strategic planning is necessary if we are to continue to provide a safe and affordable food supply from controlled environment agriculture. This planning needs to assemble the pertinent questions, and develop a comprehensive set of research and development tasks to address the uncertainty in future climate changes at a specific location. From such a strategic plan, one can envision a better understanding of how science and engineering research and development can be employed to secure a bright future, and what sort of policies at regional, national and global levels need to be articulated and set forth. As a start to this process, we offer in this section some of these research requirements and anticipated engineering solutions needed in the face of global climate change.

Ventilation systems in animal buildings have to provide suitable temperature and uniform air velocity over the animals. When the weather is hot, but not so hot as to create an added thermal load to the animal, high air velocities are necessary to avoid heat stress. Higher air velocity can be achieved by using mechanical fans. However, using mechanical fans (whether ventilation or air mixing fans) requires consideration of the fans' energy consumption. An alternative approach is to focus on improved building design[137,138] and develop of a science based understanding of key factors influencing the thermal control capacity of agricultural buildings. An important improvement in airflow patterns and air velocity at animal level can be achieved by modifying the shape, location and opening of air inlets, the number of fans and their location, or the dimensions and design of the building itself. In this sense, the use of modeling techniques (e.g. Computational Fluid Dynamics, CFD, and Particle Inferential Velocometry, PIV) could contribute to the improvement of the animal building design, aiming to achieve a specific air velocity requirement[123,139-143]; but further investigation is still necessary to guarantee that computational fluid dynamics is a reliable modeling tool.

To face the negative impact of heat waves (which are becoming more frequent and more severe in the countries with moderate and warm climates), there is an urgent need for etiologists, animal scientists, engineers and veterinarians to study animal behavior and physiological responses which might be connected with housing systems and their efficiency in providing thermal comfort for individual animals. Observed behaviors and physiological responses of animals, and where appropriate the use of animal choice as a metric for objective assessment, should be considered by engineers as the basis for designing housing systems and improving their management[40,76].

Systems which offer better adjustment possibilities for individual animals allowing them to choose most suitable environmental conditions according to their actual needs resulting from health status, weight, feed consumption, etc. should be ranked higher than the system which does not offer differentiation of environment. A wealth of possibilities exist in this broad area of “precision livestock farming”[70,76,81,144,145].

Possible differences between various systems with regard to providing the “best possible thermal comfort” seem to be relatively easily recognized at sudden environment changing (dynamic conditions) when it is relatively easy to observe the reaction of animals as a group as well as the individual differences between animal responses. The animal behavior patterns observed under such conditions should serve well as the hints for designing animal housing systems[133].

One technical option to be re-examined is providing the livestock building with thermal capacity which would enable storing the “cold-thermal-energy” in diurnal or yearly cycle by means of, e.g. high efficiency ground-coupled heat pumps, water-based energy storage systems, small wind turbines, scavenged waste heat, and so-called combined heat and power (CHP) units. Important research questions are connected with both the technical solutions of the systems and the means of applied operation strategy.

Some relief in heat stress in animal buildings can be obtained by using sprinkling systems on the roof and at the ground in close proximity to the building to utilize the heat of evaporation and locally reduce temperature. The systems based on grey water flow in closed cycle should be appropriate at relatively less severe heat stress conditions, whereas fresh water would probably have to be used where there are higher cooling requirements. However, many regions will experience extreme water shortages and in these conditions such a use of water may neither be profitable, nor wise.

Finally, it should be pointed out that technological solutions are needed for the challenges of both mitigation (slowing down global warming by reducing the level of greenhouse gases in the atmosphere) and adaptation (dealing with the existing or anticipated effects of climate change), as they are referred to in climate change terminology. Animal agriculture is implicated as a causal agent in some aspects of global climate change, as it contributes slightly to increased concentrations of greenhouse gases (GHG) in the atmosphere and is recognized as a large contributor to ammonia emissions and hence a source of reactive nitrogen. Substantial pressure for advanced engineering solutions to mitigate gaseous emissions from intensive livestock and poultry production is beginning to develop, and represents another serious challenge (and opportunity) for engineering, research and development [146].

8 Summary and conclusions

Major scientific studies have shown that climate change (i.e. increasing average temperature of the Earth) is likely. With the increasing mean global temperature; the most direct effect on animals is heat stress, which has been proven to have a variety of negative effects on animal health, welfare and productivity. Different potential measures could be used in future to alleviate the increased heat stress. Some of these measures are mere adaptations or improvements of current engineering solutions. However, facing the complex challenges of global warming and climate change will probably require novel solutions, including new designs based on solid engineering judgment, development of new engineering standards and codes to guide designs, the exploration of new and superior building materials, the need for better energy management, and the development of substantially more “intelligent” control systems that will balance changing exterior disturbances, interior building loads and demands to the biological needs of the occupants of the structures.

1) There is no doubt that global warming is a reality and that its occurrence can be easily confirmed on yearly basis. Fifteen of the last sixteen years (1995-2010) ranked among the sixteen warmest years in the instrumental record of global surface temperature since 1850.

2) There is also no doubt that the main driving force for global warming is anthropogenic activity. Although some natural phenomena to some extent also affect the global warming, total net anthropogenic increase of radiative forcing is the main cause of global warming.

3) Many natural systems seem to be already affected by global warming. It could be concluded with high confidence that anthropogenic warming over the last three decades has had a discernible influence on many physical and biological systems.

4) The impact of climate change has not been evenly distributed in the world, and this trend is expected to accelerate. Developing countries tend to be more vulnerable to climate change events than developed countries, due to the vulnerability of their economies and the direct costs of some means of adaptation. Thus climate change could ultimately exacerbate income inequalities between and within countries resulting in social instability.

5) The actual air temperatures for considerably long periods in summer happen to be significantly higher than assumed according to TRY extremely hot temperatures. The differences are high enough to justify carrying out thorough research updating existing TRY extremely hot temperatures.

6) The effects of persistent extreme heat events in moderate climate countries on the thermal conditions of livestock buildings are detrimental and could undermine livestock productivity, animal health and welfare. Thus concentrated international research is required to update our current engineering approach to the control of thermal environment in livestock buildings.

[References]

[1] Staszczuk A, Kuczyński T, Radoń J. Possible effect of hot weather periods in moderate climate regions on approach to thermal design of one-storey residential buildings. Accepted for publishing in proceedings of 9th Nordic Symposium on Building Physics. Tampere. 29th May and 2nd June 2011.

[2] IPCC. Climate Change 2007: Climate Change 2007: The Physical Science Basis, Technical Summary. 2007a (Fig.T.S.5 and T.S.6).

[3] IPCC. Climate Change 2007. Historical Overview of Climate Change. Jiang, M, K.G. Gebremedhin, and L.D. Albright. 2004. Numerical simulation of coupled heat and mass transfer through the hair coat. ASAE Annual International Meeting. St. Joseph, MI. Paper No. 044038. 2007e.

[4] Trenberth K. Earth System Processes, Volume 1, The Earth system: physical and chemical dimensions of global environmental change,. Edited by Dr Michael C MacCracken and Dr John S Perry in Encyclopedia of Global Environmental Change, 2002; 13–30

[5] IPCC. Climate Change 2007. The Physical Science Basis. Summary for Policymakers. 2007b.

[6] TAR. Third Assessment Report of the Intergovernmental Panel on Climate Change, 2001.

[7] Nienaber J A, Hahn G L. Engineering and management practices to ameliorate livestock heat stress. In: Proceedings, International Symposium of The CIGR. New Trends In Farm Buildings, Lecture 6, 1-18. May 2–6, 2004, Evora, Portugal. 2004 CdRom. 2004.

[8] Battisti D, Naylor R. Historical warnings of future food insecurity with unprecedented seasonal heat. Science, 2009; 323(5911): 240–244.

[9] IPCC. Climate Change 2007. Impacts, Adaptation and Vulnerability. Summary for Policymakers. 2. 2007c.

[10] IPCC. Climate Change 2007. Impacts, Adaptation and Vulnerability. Technical Summary. 2007d.

[11] SRES. In: Nakicenovic, N., Swart, R. (Eds.), Special Report on Emissions Scenarios. World Meteorological Organization, Geneva. 2000.

[12] Stainforth D A, Aina T, Christensen C, Collins M, Faull N, Frame D J, et al. Uncertainty in predictions of the climate response to rising levels of greenhouse gases, Nature, 2005; 433, 403–406.

[13] McGregor K M. Impact of climatic change on agricultural production in Kansas: a fourcrop analysis. Physical Geography, 1993; 14(6): 551–565.

[14] Easterling W E, Crosson P R, Rosenberg N J, McKenny M, Katz L A, Lemon K. Agricultural impacts of and responses to climate change in the Missouri-Iowa-Nebraska-Kansas (MINK) region, Washington, DC, 1993; 221–228.

[15] Frank K L, Mader T L, Harrington J A, Hahn G L, Davis M S. Climate Change Effects on Livestock Production in the Great Plains. In Livestock Environment VI, 351–358 Louisville Kentucky: The Society for engineering in agricultural, food, and biological systems, 2001.

[16] Smith B, Mc Nabb D, Smihers J. Agricultural adaptation to climatic variation. Climatic change, 1996; 33: 7–29.

[17] Baker B, Viglizzo J F. Rangelands and livestock. Chapter 9 in: Feenstra, J.F; Burton I; Smith, J.B.; Tol, R.S.J. (eds.)

Handbook of methods for climate change impact assessment and adaptation strategies. IVM/UNEP Version 2.0. 1998. http://130.37.129.100/ivm/pdf/handbook_range.pdf Accessed September 22nd. 2002.

[18] Topp C F E, Doyle C J. Simulating the impacts of global warming on milk and forage production in Scotland. 1. The effects on dry matter yield of grass and grass-white clover stands. Agricultural Systems, 1996; 52: 213–242.

[19] Campbell B D, McGeon G M, Gifford R M, Clark H, Stafford Smith D M, Newton P C D, et al. Impacts of atmospheric composition and climate change on temperate and tropical pastoral agriculture. In: Pearman, G.; Manning, M. (eds.) Greenhouse 94. CSIRO, Canberra, Australia. 1995.

[20] Reilly J. Agriculture in a changing climate: impacts and adaptation. In: Watson, R.T; Zinyowera, M.C; Moss, R.H. (Eds.) Climate change 1995: Impacts, adaptations and mitigation of climate change: Scientific-technical analyses. Cambridge University Press, USA. 1996; 427–467p.

[21] Banhazi T M, Black J L. Precision livestock farming: a suite of electronic systems to ensure the application of best practice management on livestock farms. Australian Journal of Multi-disciplinary Engineering, 2009; 7(1): 1–14.

[22] Nissim S. Effects of heat stress on the welfare of extensively managed domestic ruminants. Livestock Production Science, 2000; 67: 1–18.

[23] Bridges T C, Gates R S. Chapter 7: Modeling of Animal Bioenergetics for Environmental Management Applications. In: Livestock Energetics and Thermal Environmental Management, ASABE: St. Joseph, MI. 2009. pp. 151–179 of 209.

[24] Pang Z, Li B, Xin H, Yuan X, Wang C. Characterization of an experimental watercooled cover for sows. Biosystems Engineering, 2010; 105(2010): 439–447.

[25] Collins K H, Weiner H S. Endocrinological aspects of exposure to high environmental temperature. Physiol. Rev. 1968; 48: 785–794.

[26] Niwano Y, Becker B A, Mitra R, Caldwell CW, Abdalla E B, Johnson H D. Suppressed peripheral blood lymphocyte blastogenesis in pre- and postpartal sheep by chronic heat-stress, and suppressive property of heat-stressed sheep serum on lymphocytes. Dev. Comp. Immunol, 1990; 14, 139–149.

[27] Fuquay J W. Heat stress as it affects animal production. J Anim Sci, 1981; 52, 164–174.

[28] W1173: Stress Factors of Farm Animals and Their Effects on Performance, October 2006.

[29] COPA/COGECA. Comitê dês Organisations Professionalles de la Agricoles de la Communité Européenne / Comitê General de la Cooperation Agricole. Assessment of the impact of the heat wave and drought of the Summer 2003 on agricultural and forestry. Cologne, Alemanha. 2004. 15 p.

[30] St-Pierre N R, Cobanov B, Schnitkey G. Economic losses from heat stress by livestock industries. Journal of Dairy Science, E. Suppl., 2003; E52 – E77.

[31] Oliver J C, Hellman H M, Bishop S E, Pelissier C L, Bennett L F. Heat stress survey. Calif. Agric, 1979; 33: 6-8.

[32] Brown-Brandl T M, Yanagi T, Xin H, Gates R S, Bucklin R, Ross G. 2001. Telemetry system for measuring core body temperature in livestock. Paper No. 014032, ASAE International Mtg, Sacramento CA.

[33] Brown-Brandl T, Yanagi Jr Y, Xin H, Gates R S, Bucklin R A, Ross G S. A new telemetry system for measuring core body temperature in livestock and poultry. Applied Engineering in Agriculture, 2003a; 19(5): 583–589.

[34] Davis M S, Mader T L, Holt S M, Parkhurst A M. Strategies to reduce feedlot cattle heat stress: effects on tympanic temperature. J. Anim. Sci., 2003; 81: 649.

[35] Davis J D, Purswell J L, Bicudo J R, Vanzant E S, Gates R S. Methods of remote, continuous temperature detection in beef cattle. ASAE Paper No MC04-202, Mid-Central Section of the ASAE, St. Joseph MI, 25-26 March 2004.

[36] Spain J N, Spiers D E, Sampson J D. A study to compare nighttime cooling strategies on commercial dairy. Proc. 6th Int. Livestock Symposium. 2001a. 41p.

[37] Spain J N, Spiers D E, Sampson J D. The effects of nighttime versus continuous- cooling on thermal balance and milk production of lactating dairy cows. Proc. 6th Intl. Livestock Symposium. 2001b. 56 p.

[38] Hillman P, Willard S, Lee C N, Kennedy S D. Efficacy of a vaginal temperature logger to record body temperatures of dairy cows. ASAE Annual International Meeting. Las Vegas, NV. July 28-July 30, 2003, Paper No. 034011.

[39] Green A R, Gates R S, Lawrence L M. Measurement of horse core body temperature. J. Thermal Biol., 2005; 30(1): 370–377.

[40] Green A R, Wathes C M, Demmers T G M, MacArthur-Clark J, Xin H. A Novel Test Chamber for Laboratory Mice. Fourth International Workshop on Smart Sensors in Livestock Monitoring (SMART2006). September 22-23, Gargnano, Italy. 2006.

[41] Purswell J L, Gates R S, Lawrence L M, Jacob J D, Stombaugh T S, Coleman R J. Air exchange rate in a horse trailer during road transport. Transactions of the ASAE, 2006; 49(1) 193-201.

[42] Purswell J L, Gates R S, Lawrence L M, Davis J D. Thermal environment in a four-horse slant-load trailer. Transactions of the ASABE, 2010; 53(6):1885-1894.

[43] Brown-Brandl T M, Jones D D, Woldt W E. Evaluating modeling techniques for livestock heat stress prediction. ASAE Paper, 2003c, No. 034009. St. Joseph, MI.

[44] Bowers S, Gandy S, Anderson B, Ryan P, Willard S. Assessment of pregnancy in the mare using digital infrared thermography. J. Anim. Sci., 2004; 82(Suppl. 1):371.

[45] Schmidt S, Bowers S, Graves K, Carroll R, White J, Willard S T. Use of digital infrared thermography to assess thermal temperature gradients and pathologies of the bovine claw. J. Dairy Sci., 2003; 86(Suppl. 1): 322.

[46] Schmidt S, Bowers S, Dickerson T, Graves K, Willard S. Assessments of udder temperature gradients pre- and post-milking relative to milk production in Holstein cows as determined by digital infrared thermography. J. Anim. Sci., 2004; 82(Suppl. 1): 460.

[47] Hillman P E, Gebremedhin K G, Parkhurst A, Fuquay J, Willard S. Evaporative and convective cooling of cows in a hot and humid environment. Livestock Environment VI: Proc. 6th Intern .Symp. Louisville, KY. 2001a. 343 p. Available: http://www.nimss.umd.edu/homepages/outline.cfm?trackID=7597.

[48] Pollard B C, Dwyer M E, Fitzgerald A C, Gentry P C, Henderson D A, Collier R J. Effects of ambient temperature and solar radiation on skin evaporative water loss in dairy cattle. J. Dairy Sci., 2004; 82(Suppl 1): 98.

[49] Hahn L, Mader T, Spiers D, Gaughan J, Nienaber J, Eigenberg R, et al. Heat wave impacts on feedlot cattle: Considerations for improved environmental management. Proc. 6th Intl. Livest. Envir. Symp., Amer. Soc. Agric. Eng., St. Joseph, MI. 2001.129 p.

[50] Hillman P E, Lee C N, Carpenter J R, K.S. Baek, and A. Parkhurst. Impact of hair color on thermoregulation of dairy cows to direct sunlight. ASAE Annual International Meeting. Las Vegas, NV. Jul 29 - Aug 1, 2001b, Paper No. 014031.

[51] Parkhurst A M, Spiers D A, Mader T L, Hahn G L. Spline models for estimating heat stress thresholds in cattle. Proc. 14th Annual Kansas State University Conference on Applied Statistics in Agriculture. Manhattan. 2002. 137 p.

[52] Lan L, Parkhurst A M, Spiers D A, Eskridge K M, Hahn G L. "Using Nonlinear Fixed and Mixed Models to Study Acclimation to Heat Stress in Cattle" Proc. 14th Annual Kansas State University Conference on Applied Statistics in Agriculture. Manhattan. 2002. 149 p.

[53] Brown-Brandl T M, Nienaber J A, Hahn G L, Eigenberg R A, Parkhurst A M. Dynamic responses of feeder cattle to simulated heat waves. Pages 335-338 in Proc. Progress in Research on Energy and Protein Metabolism, EAAP Pub No. 109, Rostock, Germany. 2003b.

[54] Kerek M, Parkhurst A M, Mader T L. Using the bi-logistic model to estimate body temperature in feedlot cattle. Proc. 15th Annual Kansas State University Conference on Applied Statistics in Agriculture, Manhattan. 2003. 206 p.

[55] Eigenberg R A, Nienaber J A, Brown-Brandl T M. Development of a livestock safety monitor for cattle. ASAE Paper No. 032338. St. Joseph, MI. 2003.

[56] Hahn G L, Mader L, Eigenberg R A. Perspectives on development of thermal indices for animal studies and management. Proc. Interactions Between Climate and Animal Production, EAAP Technical Series No. 7, Viterbo, Italy. 2003. 31 p.

[57] Freetly H C, Nienaber J A, Brown-Brandl T M. Heat production of growing heifers that differ in composition of Bos Indicus and Bos Taurus. Proc. Progress in Res. on Energy and Protein Metab. EAAP Pub. # 109, Rostock, Germany. 2003a. 497 p.

[58] Freetly H C, Nienaber J A, Brown-Brandl T M. Relationship between aging and nutritionally controlled growth rate on heat production of heifers. J. Anim. Sci. 81:1847.

[59] Hillman P.E., C.N. Lee and S.T. Willard. 2005. Body temperature versus microclimate selection in heat stressed dairy cows. Trans. Am. Soc. Agric. Eng., 2003b; 48(2): 795.

[60] Oetting E, Spain J, Sampson J. The effects of strategic cooling on thermal balance of late gestation dairy cows. J. Dairy Sci., 2002; 85(Suppl. 1): 309.

[61] Spurlin K M, Spiers D E, Ellersieck M, Spain J N. Effects of simultaneous evaluation of cooling strategies on production responses and intake behavior during heat challenge in dairy cattle. J. Dairy Sci., 2002; 85(Suppl. 1) 206.

[62] Collier R J, Annen E L, Armstrong D E, Wolfgram A L. Evaluation of two evaporative cooling systems for dairy cattle under semi-arid conditions. J. Anim. Sci., 2003a; 81(Suppl 1) 18.

[63] Collier R J, Byatt J C, Denham S C, Eppard P J, Fabellar A C, Hintz R L, et al. Effects of sustained release bovine somatotropin, (Sometribove) on Animal Health in Commercial Dairy Herds. J. Dairy Sci., 2001; 84:1098–1108.

[64] Keister A, Collier R, Ax R. Follicular growth in lactating cows receiving recombinant Bovine somatotropin, gonadotropin releasing hormone and prostaglandins: Contrasts between winter and summer months. J. Dairy Sci., 2001; 84(Suppl.1): 268.

[65] Kolath S J, Coussens P M, Sipkovsky S, Wilson S J, Spiers D E, Spain J N, et al. Microarray analysis of gene expression in dominant ovarian follicles (DF) from heat

stress (HS) and thermoneutral (TN) heifers. 36th Annual Meeting Midwestern Section American Society of Animal Science. Des Moines, Iowa. 2003.

[66] Collier R J, Kobayashi Y, Gentry P. The use of genomics in genetic selection programs for environmental stress tolerance in domestic animals. Proc. 15th Conf. Biometeorol. and Aerobiol. Am. Meteorol. Soc. Press. 2003b. 54 p.

[67] Rhoads R P, Sampson J D, Tempelman R J, Sipkovsky S S, Coussens P M, Lucy M C, et al. Hepatic gene expression profiling in lactating dairy cows during an initial period of hyperthermia. J. Anim. Sci., 2004; 82(Suppl. 1) 461.

[68] Yanagi T, Xin H, Gates R S. A research facility for studying poultry responses to heat stress and its relief. Applied Engineering in Agriculture, 2002a; 18(2): 255.

[69] Chepete H J, Xin H. Ventilation rates of laying hen houses based on new vs. old heat moisture production data. Applied Engineering in Agriculture, 2004a; 20(6): 835–842.

[70] Green A R, Xin H. Effects of stocking density and group size on thermoregulatory responses of laying hens under heat challenging conditions. Transactions of the ASABE, 2009a; 52(6): 2033–2038.

[71] Chepete H J, Xin H. Alleviating heat stress of laying hens by intermittent partial surface cooling. Transactions of the ASAE, 2000; 43(4): 965–971.

[72] Tao X, Xin H. Surface wetting and its optimization to cool broiler chickens. Transactions of the ASAE, 2003a; 46(2): 483–490.

[73] Yanagi T, Xin H, Gates R S. Optimization of partial surface wetting to cool caged laying hens. Transactions of the ASAE, 2002b; 45(4): 1091.

[74] Puma M C, Xin H, Gates R S, Burnham D J. An instrumentation system for studying feeding and drinking behavior of individual poultry. Applied Engineering in Agriculture, 2001; 17(3): 365–374.

[75] Xin H, Gates R S, Puma M C, Ahn D U. Drinking water temperature effects on laying hens subjected to warm cyclic environments. Poultry Science, 2002; 81: 608–617.

[76] Gates R S, Xin H. Extracting poultry behavior from time-series weigh scale records. 2008. Computers & Electronics in Agriculture, 2008; 62(1): 8–14.

[77] Persyn K E, Xin H, Nettleton D, Ikeguchi A, Gates R S. Feeding behaviors of laying hens with or without beak-trimming. Transactions of the ASAE, 2004; 47(2) 591–596.

[78] Chepete H J, Xin H. Heat and moisture production of poultry and their housing systems: Literature review. Transactions of the ASHRAE, 2002; 108(2): 448–466.

[79] Chepete H J, Xin H. Heat and moisture production of poultry and their housing systems: Molting layers. Transactions of the ASHRAE, 2004b; 110(2): 274–285.

[80] Chepete H J, Xin H, Puma M C, Gates R S. Heatand moisture production of poultry and their housing systems: Pullets and layers. Transactions of the ASHRAE, 2004; 110(2): 286–299.

[81] Green A R, Xin H. Effects of stocking density and group size on heat and moisture production of laying hens under thermoneutral and heat challenging conditions. Transactions of the ASABE, 2009; 52(6): 2027–2032.

[82] Brown-Brandl T, Nienaber J A, Xin H, Gates R S. A literature review of swine heat production. Trans ASAE, 2004; 47(1): 259–270.

[83] Olanrewaju H A, Purswell J L, Collier S D, Branton S L. Effect of Ambient Temperature and Light Intensity on Physiological Reactions of Heavy Broiler Chickens. Poultry Science, 2010a; 89: 2719–2725.

[84] Olanrewaju H A, Purswell J L, Collier S D, Branton S L. Effect of ambient temperature and light Intensity on growth performance and carcass characteristics of heavy broiler chickens at 56 days of age. International Journal of Poultry Science, 2010b; 9(8): 720–725.

[85] Arthington J D, Eicher S D, Kunkle W E, Martin F G. Effect of transportation and commingling on the acute phase protein response, growth and feed intake of newly weaned beef calves. J. Anim. Sci., 2003; 81: 1136–1141.

[86] Arthington J D, Spears J W, Miller D C. The effect of early weaning on feedlot performance and measures of stress in beef calves. J. Anim. Sci., 2005; 83:933–939.

[87] Green A R, Gates R S, Lawrence L M. Equine thermoregulatory responses during summertime road transport and stall confinement. Brazilian Journal of Biosystems Engineering, 2007; 1(1): 83–92.

[88] Friend T H, Giguere N M, Krawczel P D. Cross ventilation in commercial livestock trailers shows promise for improving comfort, reducing weight loss and reducing environmental contaminants. J. Animal Science 85, Suppl 1, 2007; 36 p.

[89] Hutcheson D P, Cole N A. Management of transit stress syndrome in cattle: Nutritional and environmental effects. J. Anim. Sci., 1986; 62: 555.

[90] Johnson H D. Bioclimate effects on growth, reproduction and milk production. In: Bioclimatology and the adaptation of livestock, Elsevier, Amsterdam, The Netherlands. Part II, Chapter 3. 1987.

[91] Valtorta S E, Maciel M. Respuesta reproductiva. In: Producción de leche em verano. Centro de publicaciones de la Secretaría de Extensión de la UNLitoral, Santa Fe, Argentina, 1998; 64–76.

[92] Valtorta S E, Gallardo M R, Castro H C, Castelli M C. Artificial shade and supplementation effects on grazing dairy cows in Argentina. Trans. ASAE, 1996; 39: 233–236.

[93] Valtorta S E, Leva P E, Gallardo M R, Scarpati O E. Milk production responses during heat waves events in Argentina. 15th Conference on Biometeorology and Aerobiology - 16th International Congress on Biometeorology. Kansas City, MO. American Meteorological Society, Boston, 2002. 98–101.

[94] Berry I L, Shanklin M D, Johnson H D. Dairy shelter design based on milk production decline as affected by temperature and humidity. Trans. ASAE, 1964; 7, 329.

[95] Lima K A O, Moura D J, Naas I A, Perissinoto M. Estudo da influência de ondas de calor sobre a produção de leite no estado de São Paulo. Brazilian Journal of Biosystems Engineering, 2007; 1: 71–82.

[96] Mount L E. The Climatic Physiology of the Pig. Williams and Wilkins, Baltimore. 1968.

[97] Morrison W D, Bate L A, McMillan I, Amyot E. Operant Heat Demand of Piglets Housed on Four Different Floors. Canadian Journal of Animal Science, 1987; 67, 337–341.

[98] Tao X, Xin H. Acute, synergistic effects of air temperature, humidity and velocity on homeostasis of market-size broilers. Transactions of the ASAE, 2003b; 46(2): 491–497.

[99] Curtis S E, Morris G L. Operant Supplemental Heat in Swine Nurseries. Livestock Environment II. Proceedings of the 2nd International Livestock Environment Symposium. St. Joseph, Michigan, 1982; 295–297.

[100] Pedersen S, Takai H H. Diurnal Variation in Animal Heat Production in Relation to Animal Activity. Livestock Environment V. Proc. of the Fifth International Symposium. Bloomington, St. Joseph, Michigan, 1997; 664-671.

[101] Leenstra F, Cahaner A. Genotype by Environment Interactions Using Fast Growing, Lean or Fat Broiler Chickens, Originating from the Netherlands and Israel, Raised at Normal or low Temperature. Poultry Science, 1991; 70, 2028–2039.

[102] Leenstra F, Cahaner A. Effects of Low, Normal and High Temperatures on Slaughter Yield of Broilers from Lines Selected for High Weigh Gain, Favorable Feed Conversion, and High or Low Fat Content. Poultry Science, 1992; 71, 1994–2006.

[103] May J D, Lott B D, Simmons J D. The effect of environmental temperature and body weight on growth rate and feed; gain of male broilers. Poultry Science, 1998; 77, 499–501.

[104] Timmons M B, Gates R S, Bottcher R W, Carter T A, Brake J T, Wineland M J. Simulation analysis of a new temperature control method for poultry housing. Journal of Agricultural Engineering Research, 1995; 62(4): 237–245.

[105] Knight C D, Weulling C W, Atwell C A, Dibner J J. Effect of Intermittent Periods of High Environmental Temperature on Broiler Performance Responses to Sources of Methionine Activity. Poultry Science, 1994; 73, 627–639.

[106] Silanikove N, Gutman M. Interrelationships between lack of shading shelter and poultry litter supplementation: feed intake, body weight, water metabolism and embryo loss in beef cows grazing dry Mediterranean pasture. Anim. Prod. 1992; 55, 371–376.

[107] Banhazi T, Cargill C, Harper Z, Wegiel J, Glatz P. The effects of drinking water temperatures on pig production. In AgriBuilding, Naas I A(Ed). Campinas, Brazil: University of Campinas, 2001; (1): 157–162.

[108] West J W. Nutritional strategies for managing the heat stressed dairy cow. J. Anim. Sci., 1999; 77 (Suppl. 2): 21–35.

[109] Li B. Adaptability of an evaporative pad cooling system to the weather conditons of China. In: Zhang W, Guo P, Zhang S(Ed.), Agricultural engineering and rural development. Proceedings of International Conferences on Agricultural Engineering, 1992; (92-ICAE): 71–74.

[110] Turner L W, Chastain J P, Hemken R W, Gates R S, Crist W L. Reducing heat stress in dairy cows through sprinkler and fan cooling. Applied Engineering in Agriculture, 1992; 8(2): 251–256.

[111] Timmons M B, Gates R S. Predictive model of evaporative cooling and laying hen performance to air temperature and evaporative cooling. Transactions of the ASAE, 1988; 31(5): 1503–1509.

[112] Bridges T C, Gates R S, Turner L W. Stochastic assessment of evaporative misting for growing-finishing swine in Kentucky. Applied Engineering in Agriculture, 1992; 8(5): 685–693.

[113] Bridges T C, Turner L W, Gates R S. Economic evaluation of misting-cooling systems for growing/finishing swine through modeling. Applied Engineering in Agriculture, 1998; 14(4): 425–430.

[114] Bridges T C, Turner L W, Gates R S, Overhults D G. Assessing the benefits of misting-cooling systems for growing/finishing swine as affected by environment and pig placement date. Applied Engineering in Agriculture, 2003; 19(3): 361–366.

[115] Gates R S, Zhang H, Colliver D G, Overhults D G. Regional variation in temperature humidity index for poultry housing. Transactions of the ASAE, 1995; 38(1): 197–205.

[116] Gates R S, Timmons M B. Method to assess economic risk applied to environmental control options for animal housing. Transactions of the ASAE, 1988a; 31(1): 197–201.

[117] Gates R S, Timmons M B. Stochastic and deterministic analysis of evaporative cooling benefits for laying hens. Transactions of the ASAE, 1988b; 31(3): 904–909.

[118] Timmons M B, Gates R S. Temperature dependent efficacy of evaporative cooling for broilers. Transactions of the ASAE, 1989; 5(2): 215–224.

[119] Gates R S, Overhults D G, Bottcher R W, Zhang S H. Field calibration of a transient model for broiler misting. Transactions of the ASAE, 1992; 35(5): 1623–1631.

[120] Gates R S, Timmons M B, Bottcher R W. Numerical optimization of evaporative misting systems. Transactions of the ASAE, 1991a; 34(1): 575–580.

[121] Gates R S, Usry J L, Nienaber J A, Turner L W, Bridges T C. Optimal misting method for cooling livestock housing. Transactions of the ASAE, 1991b; 34(5): 2199–2206.

[122] Bottcher R W, Baughman G R, Gate s R S, Timmons M B. Characterizing efficiency of misting systems for poultry. Transactions of the ASAE, 1991; 34(2): 586–590.

[123] Blanes-Vidal V, Guijarro E, Balasch S, Torres A G. Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building. Biosystems Engineering, 2008; 100(1): 105–116.

[124] Loot B D, Simmons J D, May J D. Air velocity and high temperature effects on broiler performance. Poultry Science, 1998; 77(3): 391–393.

[125] Yahav S, Straschnow A, Vax E, Razpakovski V, Shinder D. Air velocity alters broiler performance under harsh environmental conditions. Poultry Science, 2001; 80(6): 724–72.

[126] Yahav S, Straschnow A, Luger D D, Tanny Shinder J, Cohen S. Ventilation, sensible heat loss, broiler energy, and water balance under harsh environmental conditions. Poultry Science, 2004; 83(2): 253–258.

[127] Dozier W A, Purswell J L, Branton S L. Growth responses of male broilers subjected to high air velocity for either twelve or twenty-four hours from thirty-seven to fifty-one days of age. Journal of applied poultry research, 2006; 15, 362–366.

[128] Blanes-Vidal V, Fitas V, Torres A. Differential pressure as a control parameter for ventilation in poultry houses: Effect on air velocity in the zone occupied by animals. Spanish J. Agric. Res. 2007; 5(1): 31–37.

[129] Wheeler E F, Zajaczkowski J L, Saheb N C. Field evaluation of temperature and velocity uniformity in tunnel and conventional ventilation broiler houses. Applied Engineering in Agriculture, 2003;19(3): 367–377.

[130] Czarick M, Tyson B L. Design Considerations for Tunnel-Ventilated Broiler Houses. ASAE paper No. 89-4527, St. Joseph, MI 49085–9659. 1989.

[131] Bottcher R W, Czarick M. Tunnel ventilation and evaporative cooling for poultry. North Carolina Cooperative Extension Service, AG-554. 1997.

[132] Bottcher R W, Baughman G R, Munilla R D, Grimes J L, Gonder E. Development of a large paddle fan for cooling poultry. Applied Engineering in Agriculture, 1998; 14(1): 87–96.

[133] Kuczyński T. Poultry Behaviour Response on Heat Stress and its Potential Application for Improving its Welfare. [In:] Animal Welfare Considerations in Livestock Housing Systems. Proceedings of the International Symposium. Szklarska Poręba-Zielona Góra (Poland), 200; 353–364.

[134] Shi Z, Li B, Zhang X, Wang C, Zhou D, Zhang G. Using floor cooling as an approach to improving the thermal environment in the sleeping area in an open pig house. Biosystems Engineering, 2006; 93(3): 359–364.

[135] Cummins K. Bedding plays role in heat abatement. Dairy Herd Manag. 6 (June), 1998;20. 36: 77–87.

[136] Dong H, Tao X, Lin J, Xin H. Comparative evaluation of cooling systems for farrowing sows. Appl. Engineering. Agri., 2001; 17 (1): 91–96.

[137] Banhazi T, Rutley D, Glatz P. Factors effecting thermal conditions in piggery buildings in South Australia. In New trends in farm buildings, 2004; Vol. 1, CD publication (Eds Meneses J, Silva L, Baptista F J, Cruz V). Evora, Portugal: University of Evora.

[138] Banhazi T. Influence of piggery building construction and management on thermal control in Australia. In CIGR Wold Congress, Vol. 1(Ed A. Munack). Germany, Bonn: VDI. 2006.

[139] Li Dongning, Zhang Y, Sun Y, Wei Yan. A multi-frame particle tracking algorithm robust against input noise. J. Measurement Science and Technology, 2008; 19: 1–11.

[140] Lee S Sase, Sung S H. Evaluation of CFD accuracy for the ventilation study of a naturally ventilated broiler house, Japan Agricultural Research Quarterly, 2007; 41(1): 53–64.

[141] Sun Y, Zhang Y. Development of a stereoscopic particle image velocimetry system for full-scale room airflow studies, Part II: Experimental setup. Transactions of Amer. Soc. Heat. Refrig. Air Cond. Engr, 2003; 109(2): 540–548.

[142] Sun Y, Zhang Y. An algorithm of stereoscopic particle image velocimetry for full-scale room airflow studies. Transactions of Amer. Soc. Heat. Refrig. Air Cond. Engr., 2004; 110(1): 85–90.

[143] Zhao L Y, Zhang Y, Wang X, Riskowski G L, Christianson L L. Measurement of two-dimensional air velocities in a full-scale room using particle image velocimetry. Transactions of Amer. Soc. Heat. Refrig. Air Cond. Engr., 2001; 107(2): 434–444.

[144] Banhazi T, Dunn M, Cook P, Black J, Durack M, Johnnson I. Development of precision livestock farming (PLF) technologies for the Australian pig industry. In 3rd European

Precision Livestock farming Conference, Vol. 1. (Ed S. Cox), 2007; 219–228. Skiathos, Greece: University of Thessaly.

[145] Banhazi T M, Aarnink A, Thuy H, Pedersen S, Hartung J, Payne H, et al. Review of the consequences and control of high air temperatures in intensive livestock buildings. Australian Journal of Multi-disciplinary Engineering, 2009; 7(1): 63–78.

[146] Banhazi T M, Rutley D L, Pitchford W S. Identification of risk factors for sub-optimal housing conditions in Australian piggeries-Part IV: Emission factors and study recommendations. Journal of Agricultural Safety and Health, 2008; 14(1): 53–69.