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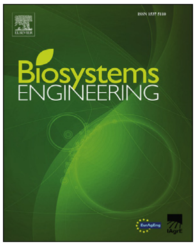

Research Paper

Uncertainty in the measurement of indoor temperature and humidity in naturally ventilated dairy buildings as influenced by measurement technique and data variability

Sabrina Hempel [a,*], *Marcel König* [a], *Christoph Menz* [b], *David Janke* [a], *Barbara Amon* [a], *Thomas M. Banhazi* [c], *Fernando Estellés* [d], *Thomas Amon* [a,e]

[a] *Leibniz-Institute for Agricultural Engineering and Bioeconomy (ATB), Max-Eyth-Allee 100, 14469 Potsdam, Germany*
[b] *Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, 14412 Potsdam, Germany*
[c] *University of Southern Queensland, Toowoomba, Queensland, Australia*
[d] *Institute of Animal Science and Technology, Universitat Politecnica de Valencia, Camino de Vera S/n, 46022, Valencia, Spain*
[e] *Department Veterinary Medicine, Free University Berlin, Robert-von-Ostertag-Str. 7-13, 14163 Berlin, Germany*

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The microclimatic conditions in dairy buildings affect animal welfare and gaseous emissions. Measurements are highly variable due to the inhomogeneous distribution of heat and humidity sources (related to farm management) and the turbulent inflow (associated with meteorologic boundary conditions). The selection of the measurement strategy (number and position of the sensors) and the analysis methodology adds to the uncertainty of the applied measurement technique.

To assess the suitability of different sensor positions, in situations where monitoring in the direct vicinity of the animals is not possible, we collected long-term data in two naturally ventilated dairy barns in Germany between March 2015 and April 2016 (horizontal and vertical profiles with 10 to 5 min temporal resolution). Uncertainties related to the measurement setup were assessed by comparing the device outputs under lab conditions after the on-farm experiments.

We found out that the uncertainty in measurements of relative humidity is of particular importance when assessing heat stress risk and resulting economic losses in terms of temperature-humidity index. Measurements at a height of approximately 3 m–3.5 m turned out to be a good approximation for the microclimatic conditions in the animal occupied zone (including the air volume close to the emission active zone). However, further investigation along this cross-section is required to reduce uncertainties related to

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[*] *Corresponding author.*

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the inhomogeneous distribution of humidity. In addition, a regular sound cleaning (and if possible recalibration after few months) of the measurement devices is crucial to reduce the instrumentation uncertainty in long-term monitoring of relative humidity in dairy barns.

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Nomenclature

NVB	naturally ventilated barn
THI	temperature-humidity index
T	temperature, °C
H	relative humidity, %
t	time (dependent on the content in seconds or in days)
ρ_τ	autocorrelation for lag τ
τ	time lag
E	expected value operator
σ	variance of time series
x	time series
$\bar{x}$	mean value of the time series
N	length of the time series
P	power spectral density
f	frequency
n_q	Nyquist frequency
ΔT	sampling interval
U	uncertainty
i, j, k	indices for uncertainty estimation indicating time point, sensor and random number
r	realisation of the random process
DT	Dummerstorf
GK	Gross Kreutz
NGT	night from 10 pm to 4 am
MRNG	morning from 4 am to 10 am
NOON	noon from 10 am to 4 pm
EVE	evening from 4 pm to 10 pm

1. Introduction

Animal husbandry must be animal- and environment-friendly to be socially acceptable and sustainable. The ventilation of livestock houses is a key driver for animal welfare and pollutant emissions. It is crucial to remove pollutants, excess moisture and heat from livestock houses. Two principal options exist; the application of mechanical and natural ventilation systems.

In Europe, the economically highly relevant dairy cattle sector is predominantly characterised by intensive milk production with high-yielding cows in naturally ventilated barns (NVB) (Algers et al., 2009). The main advantage of these buildings is their energy saving property since in general natural ventilation does not require electrical energy to operate fans. However, this housing system is particularly vulnerable to climate change as the microclimate in the barn directly depends on the ambient climatic conditions.

Larger variability and more extreme conditions in the regional climate are projected under various climate change scenarios (Christensen et al., 2007). That might affect animal welfare as well as gaseous emissions. In addition, there is an indirect impact of climate change on the net production associated with the farms as, for example, an increase in management related expenses and a decrease in reproduction rate and milk yield is expected under heat stress conditions (Kuczynski et al., 2011). However, the quantification of these impacts is challenging, as the relations between the impacts and the microclimatic conditions are complex and only partly described by the documented empirical equations. Moreover, uncertainty in the monitoring of the related microclimatic key parameters (temperature, humidity and local air velocity) will increase uncertainties in the impact assessment.

Classically, heat stress is assessed by a temperature-humidity index (THI) which is based on point measurements of air temperature and relative humidity (NRC, 1971; Armstrong, 1994; Kendall et al., 2006). Sometimes additional variables are taken into account that can increase or decrease the heat load such as radiation or air speed (Mader, Davis, & Brown-Brandl, 2006). The THI increase is associated with decreases in dry matter intake, milk yield and milk quality as well as an increase in water consumption (Bohmanova, Misztal, & Cole, 2007; Bouraoui, Lahmar, Majdoub, Djemali, & Belyea, 2002; Carabano et al., 2016). It is also documented in literature that rising THI values result in a reduction in milk fat and protein content (Ravagnolo, Misztal, & Hoogenboom, 2000). These impacts can be translated into economical losses on the farm.

Moreover, the microclimatic conditions in a barn affect the emissions that are attributed to the barn, as outlined hereafter.

Ammonia release from the floor of cattle houses, for example, is strongly affected by air and manure temperature and by air velocity and turbulence intensity above the ammonia releasing surface (Bjerg et al., 2013; Rong, Liu, Pedersen, & Zhang, 2014; Saha et al., 2014; Schrade et al., 2012). In addition, there is a relation between relative humidity of the barn air and ammonia emissions from naturally ventilated dairy barns (Saha et al., 2014). The relative humidity of the air surrounding the manure influences the humidity in the manure with low values speeding up evaporation and higher values slowing it down. The humidity in the manure, on the other hand, changes the pH level, which is again a crucial parameter for the estimation of ammonia release rates (Bjerg et al., 2013).

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