

# Study of heat-stress levels in naturally ventilated sheep barns during heat waves: development and assessment of regression models

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**Abstract** It is well documented that heat-stress burdens sheep welfare and productivity. Peak heat-stress levels are observed when high temperatures prevail, i.e. during heat waves; however, continuous measurements inside livestock buildings are not usually available for long periods so as to study the variation of summer heat-stress levels for several years, especially during extreme hot weather. A methodology to develop a long time series of summer temperature and relative humidity inside naturally ventilated sheep barns is proposed. The accuracy and the transferability of the developed linear regression models were verified. Temperature Humidity Index (THI) was used to assess sheep's potential heat-stress. The variation of THI inside a barn during heat wave and non-heat wave days was examined, and the results were comparatively assessed. The analysis showed that sheep were exposed to moderate, severe, and extreme severe heat-stress in 10, 21 and 66 % of hours, respectively, during heat wave days, while the

corresponding values during non-heat wave days were 14, 33 and 43 %, respectively. The heat load on sheep was much higher during heat wave events than during non-heat wave periods. Additionally, based on the averaged diurnal variation of THI, it was concluded that extreme severe heat-stress conditions were prevailing between 1000 and 2400 hours local time during heat wave days. Cool off night periods were never and extremely rarely detected during heat wave and non-heat wave days, respectively.

**Keywords** Sheep · Sheep barn · Heat-stress · Regression model · Temperature Humidity Index · Heat wave

## Introduction

Climate conditions inside a livestock building affect animal health and welfare. A poor thermal environment can affect the incidence and severity of certain diseases, as well as the animals' thermal comfort, growth rate, and milk yield (Sejian et al. 2012). Although sheep's small size, relative to cattle, renders them potentially able to lose heat faster and sheep are considered to be among the most heat-tolerant species (Thwaites 1985; Dwyer 2008), many studies have concluded that sheep physiology, welfare, health, and productivity are significantly affected when they are exposed to heat-stress conditions. Sevi et al. (2001) concluded that high temperatures induce adverse effects on the thermal and energy balance, the mineral metabolism, the immune function, the udder health, and the milk production of lactating ewes during summer under the Mediterranean climate. Panagakis and Chronopoulou (2010) showed that under abnormally hot summer conditions, dairy ewes had respiration rates above normal altering their shade-seeking behaviour. Papanastasiou et al. (2014) reported that in the east coast of central Greece, dairy ewes were exposed to potential heat-stress

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**Fig. 1** Map of Greece (*left*) and monitoring sites of meteorological data (*right*). The *right* map is the enlargement of the area marked with a *white* rectangle in the *left* map

in 79 % of summer hours. Additionally, heat-stress caused a significant financial burden to livestock producers by decreasing milk and meat production, decreasing reproductive efficiency, and adversely affecting livestock health (Sejian et al. 2012). On the contrary, a reduction of thermal stress in dairy sheep resulted in lengthening of lactation, maintenance of good processing features of milk, and reduction in veterinary costs (Sevi and Caroprese 2012). For sheep housed inside barns (under shade), shearing assists cooling by increasing convective loss (Macfarlane 1968). Actually, under Greek summer conditions, all sheep are shorn; therefore, fleece insulation is not of major importance. Shearing could be combined with cooling by fans equipped with water foggers to better alleviate heat-stress (Leibovich et al. 2011).

Sheep farming in Greece is the largest livestock sector and mostly oriented towards milk and cheese production (705,000 and 125,000 t, respectively; FAOSTAT 2013) both accounting for ~9 % of the total value of agricultural production.

Unfortunately, continuous indoor measurements of the thermal microenvironment are not usually available for long periods; therefore, a methodology providing the opportunity to assess summer sheep heat-stress levels for several years is needed. A common method used to achieve quantitative short-term prediction is the application of linear regression analysis. This method has been applied in many environmental studies, including studies about the livestock sector, and few of them are reported here. Haeussermann et al. (2008) applied a multiple linear regression

model to estimate average PM10 concentrations that occur in mechanically ventilated swine facilities. Coopman et al. (2009) developed linear regression models to predict the live weight of male and female double-musled Belgian blue beef farm animals using age and selections of four different body measurements. Nascimento et al. (2014) used linear regression models incorporating environmental parameters and age to predict the surface temperatures of the feathered and featherless areas of broiler chickens.

The objective of this paper was to develop a long time series of summer temperature and relative humidity values inside naturally ventilated sheep barns so as to study the variations of potential heat-stress to which sheep were exposed during heat wave (HW) days. Heat-stress conditions were assessed by means of the Temperature Humidity Index (THI), which is a widely accepted method to study animals' heat-stress.

## Materials and methods

### Climate data

Hourly averaged values of temperature and relative humidity recorded inside two naturally ventilated sheep barns and at an outdoor site were used in this study. The locations of the monitoring sites are presented in Fig. 1, while relevant information is presented in Table 1.

**Table 1** Information about the location of the monitoring sites and data temporal coverage

Monitoring site	Code name	Coordinates	Temporal coverage	Distance from (km)
Sheep barn No1	BIPE	22° 52' E–39° 23' N	August 2010, July 2011, August 2011	Dimini: 5.6
Sheep barn No2	Dimini	22° 53' E–39° 20' N	July 2009, August 2009	Velestino: 13.5
Outdoor site	Velestino	22° 45' E–39° 24' N	July and August, from 2007 to 2013	BIPE: 9

Miniature devices (Hobo Pro, Onset, USA) were used to monitor temperature and relative humidity inside the sheep barns. The devices were placed in a white plastic shield for protection and were installed at the centre of the barn at approximately 1.5 m above the floor so as to be out of animal reach. Temperature and relative humidity at the outdoor site were recorded 2 m above the ground by an automated meteorological station operated by the Laboratory of Agricultural Engineering and Environment, Institute for Research and Technology of Thessaly, Centre for Research and Technology Hellas. No missing values were found in the datasets recorded at BIPE and Dimini, while data was not available for 8 days (2 %) at Velestino.

This paper studied sheep heat-tress conditions in a lowland area. According to the Greek Ministry of Agriculture and Food (2011), 85 % of sheep farming takes place at mountainous and semi-mountainous areas resulting in low overall efficiency. It is for this reason that during the last years, sheep farming has expanded at lowland areas, where climate conditions are not favourable, especially during summer (Panagakis and Deligeorgis 2008; Panagakis and Chronopoulou 2010; Papanastasiou et al. 2014; 2015; Panagakis 2016).

### Development and validation of models

Two linear regression models were developed (Eqs. 1 and 2) and used to estimate temperature and relative humidity at BIPE ( $T_{in}$  and  $RH_{in}$ , respectively) based on temperature and relative humidity recorded at Velestino ( $T_{out}$  and  $RH_{out}$ , respectively).  $a$  and  $b$  in Eq. 1 and  $c$  and  $d$  in Eq. 2 are constants which were determined by the regression analysis. The models were validated against measurements by means of two statistical indices, namely the mean absolute error (MAE, Eq. 3) and the index of agreement (IA, Eq. 4) (Joliffe and Stephenson 2003). In Eqs. 3 and 4,  $O$ ,  $O_i$ ,  $P_i$ , and  $N$  stand for the mean of the observed values, the observed values themselves, the predicted values, and the number of data points, respectively. These indices are considered as good overall measures of model performance and have been widely used in environmental studies. MAE illustrates the presence of significant mispredictions, and IA indicates the degree to which the predictions of the model are error free. The ability of the models to predict the occurrence of each heat-stress category (see section “Estimation of sheep’s heat-stress”) was also evaluated. The validated models were used to develop the indoor temperature and relative humidity time series for July and August of the period 2007–2013. Results produced by the models were comparatively assessed to measurements recorded at Dimini

in order to check the transferability of the models in the greater area.

$$T_{in} = a \cdot T_{out} + b \quad (1)$$

$$RH_{in} = c \cdot RH_{out} + d \quad (2)$$

$$MAE = \frac{\sum_{i=1}^N |O_i - P_i|}{N} \quad (3)$$

$$IA = 1 - \frac{\sum_{i=1}^N (O_i - P_i)^2}{\sum_{i=1}^N \left( |P_i - O| + |O_i - O| \right)^2} \quad (4)$$

### Identification of HW days

The identification of a HW day was based on a temperature criterion. The criterion was based on IPCC’s definition of an extreme weather event. HWs are considered as extreme weather events. According to IPCC, “an extreme weather event would normally be as rare as or rarer than the 10<sup>th</sup> or 90<sup>th</sup> percentile of a probability density function estimated from observations” (IPCC 2013). Following this definition, the temperature criterion applied in this study exploited the 90th percentile of the daily maximum hourly values (DMHVs) of temperature, namely when the DMHV of temperature exceeded the 90th percentile, a HW day was identified. This temperature criterion was applied to the data recorded at Velestino in July and August during the period 2007–2013.

### Estimation of sheep’s heat-stress

Marai et al. (2007) suggested that an appropriate climate index to estimate the severity of sheep heat-stress is the THI given in Eq. 5, where  $T$  is the dry bulb temperature (°C) and  $RH$  is the relative humidity (%). The same authors defined four heat-stress categories which are presented in Table 2.

$$THI = T_{in} - (0.31 - 0.0031 \cdot RH_{in}) \cdot (T_{in} - 14.4) \quad (5)$$

**Table 2** Definition of heat stress categories according to THI values

THI class	Heat stress category
$THI < 22.2$	Absence of heat stress
$22.2 \leq THI < 23.3$	Moderate heat stress
$23.3 \leq THI < 25.6$	Severe heat stress
$THI \geq 25.6$	Extreme severe heat stress

**Table 3** Assessment of the model performance

	MAE (% of the mean of the observed values)	IA
Model for temperature	3.7	0.95
Model for relative humidity	10.4	0.85

THI is a very popular index which has been applied in many heat-stress assessment studies. Finocchiaro et al. (2005), Leibovich et al. (2011), Sevi et al. (2001, 2002), and Sevi and Caroprese (2012) used an almost identical formula with the one applied in this study, which, however, has been developed for cattle (Kelly and Bond, 1971). In this study, the THI definition for sheep proposed by Marai et al. (2007) was applied, because its validity has been tested under Greek summer conditions when Panagakakis and Chronopoulou (2010) found that sheep of the Chios and the Karagouniko breed, both adapted to Greek climate conditions, exhibited above normal respiration rate values, which were significantly related to this THI. Additionally, it has been applied by the authors in other papers already published in literature (Papanastasiou et al. 2014; 2015, Panagakakis 2016). Finally, the same index was very recently used by McManus et al. (2015) to classify whether the environment was moderately stressful for sheep or subjected the animals to extremely severe stress.

## Results and discussion

### Development and validation of models

Temperature and relative humidity data observed during July and August of 2011 were used to develop the two linear regression models, while data observed during August of 2010 were used to validate the models. The low values of MAE and the high values of IA (Table 3) reveal that the models are capable to simulate the indoor experimental data at BIPE. The indoor temperature and relative humidity time series produced by the models for the period July 2009–August 2009 were comparatively assessed to measurements recorded at Dimini in order to check the transferability of the time series

**Table 4** Assessment of the transferability of the models

	MAE (% of the mean of the observed values)	IA
Model for temperature	5.2	0.93
Model for relative humidity	14.6	0.84

**Table 5** 2 × 2 contingency tables for each heat stress category at BIPE (% scores)

		Absence of heat stress		Moderate heat stress		Severe heat stress		Extreme severe heat stress	
		Observed		Observed		Observed		Observed	
		Yes	No	Yes	No	Yes	No	Yes	No
Predicted	Yes	2	1	4	6	27	6	52	1
	No	1	96	2	88	7	60	6	41

in the greater area. When the produced time series were compared to measurements recorded in another sheep facility, MAEs were increased approximately 40 % (Table 4). However, MAE values still remained at low levels, while IA values remained almost the same (Table 4). Therefore, it could be concluded that the time series produced by the models can successfully predict the indoor climate conditions that prevail in other naturally ventilated sheep facilities located in the greater area, provided these facilities have similar characteristics regarding the structure (e.g. thermal insulation, ventilation rate, etc.) and the animals housed (e.g. weight, housing density, etc.). The sheep barns at BIPE and Dimini fulfil this assumption. Both of them are not insulated, they are in proximity so the wind field could be considered almost unaltered and the opening area is similar. In both barns, live weight of each housed sheep ranged between 64 and 71 kg and housing density was approximately 1.5 m<sup>2</sup> per animal.

The validation of the models was further supported by evaluating their ability to predict the occurrence of each heat-stress category at BIPE and Dimini. For this purpose, a 2 × 2 contingency table was produced for every heat-stress category observed at every sheep barn (Joliffe and Stephenson 2003). Tables 5 and 6 present the scores at BIPE and Dimini, respectively. Tables 5 and 6 show that the true predictions [i.e. (a) observed and predicted heat-stress category and (b) not observed and not predicted heat-stress category] ranged between 80 and 98 %. This fact shows that the models achieved to predict well the occurrence of each heat-stress category at both sheep barns.

**Table 6** 2 × 2 contingency tables for each heat stress category at Dimini (% scores)

		Absence of heat stress		Moderate heat stress		Severe heat stress		Extreme severe heat stress	
		Observed		Observed		Observed		Observed	
		Yes	No	Yes	No	Yes	No	Yes	No
Predicted	Yes	10	3	6	9	20	13	39	0
	No	3	84	5	80	7	60	10	51



**Table 7** Information about the number of HW days identified per year and the peak temperature levels observed during them

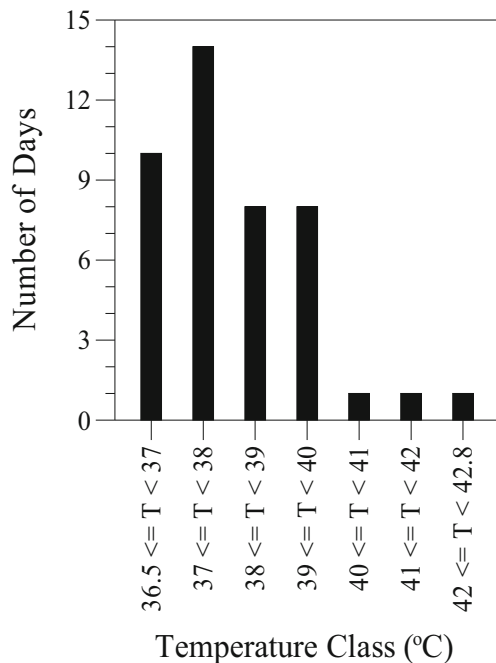
Year	2007	2008	2009	2010	2011	2012	2013
Number of HW days	9	5	3	5	2	15	4
Maximum DMHV of temperature during HW days	42.8	38.1	40.6	38.4	39.0	39.9	39.3
Minimum DMHV of temperature during HW days	36.6	36.5	37.0	36.8	37.5	36.9	36.6

**Identification of heat wave days**

The 90th percentile of the DMHVs of temperature observed at Velestino in July and August during the period 2007–2013 was found equal to 36.5 °C. The DMHV of temperature exceeded this threshold in 43 days; therefore, 43 HW days were identified. The non-HW days were 383, whereas, as already mentioned, no data were available for 8 days. Information about the number of HW days identified per year and the DMHV of temperature observed during HW days per year is provided in Table 7. The maximum DMHV of temperature was 42.8 °C, and it was observed on 25 July 2007, when the peak of a strong HW occurred (Papanastasiou et al. 2010). Figure 2 shows the distribution of the DMHVs of temperature during the HW days. Figure 2 reveals that the DMHV of temperature during more than half HW days (i.e. 24 days) ranged between 36.5 and 38 °C.

**Assessment of potential sheep heat-stress**

The indoor temperature and relative humidity time series for July and August of the period 2007–2013 produced by the models were exploited to calculate THI values in order to

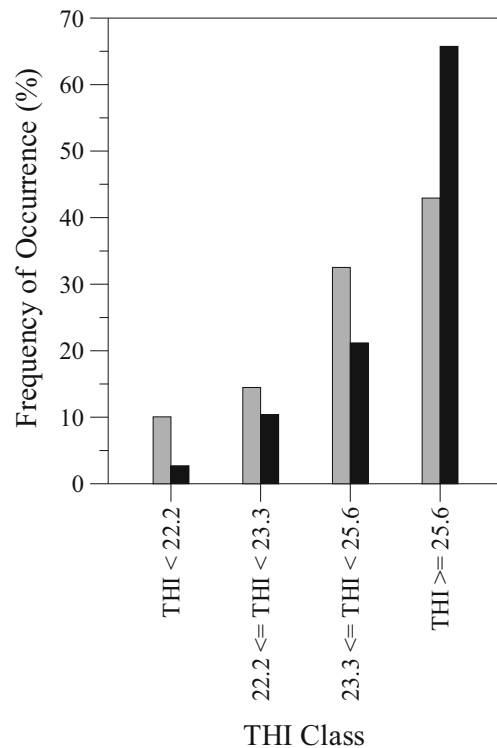


**Fig. 2** Frequency of occurrence of DMHVs of temperature during HW days

assess the heat-stress conditions to which sheep were potentially exposed during the HW days that occurred during that 7-year period. The frequency of occurrence of THI classes (heat-stress categories) during HW and non-HW days is presented in Fig. 3. Figure 3 reveals a shift to higher classes during HW days. Sheep were exposed to moderate, severe, and extreme severe heat-stress in 10, 21, and 66 % of hours during HW days, respectively, while the corresponding values during non-HW days were 14, 33, and 43 %, respectively.

Descriptive statistics for the DMHVs of THI during HW and non-HW days are presented in Table 8. The analysis revealed that the maximum value of the DMHVs of THI observed during non-HW days (i.e. 30.1) corresponded to the 25th percentile of the DMHVs of THI observed during HW days. Additionally, the minimum value of the DMHVs of THI observed during HW days (i.e. 29.7) corresponded to the 98th percentile of the DMHVs of THI observed during non-HW days.

The analysis was further expanded to study the intensity and the persistency of heat-stress. For this purpose, the Daily



**Fig. 3** Frequency of occurrence of THI classes (heat stress categories) during HW (black bars) and non-HW (grey bars) days

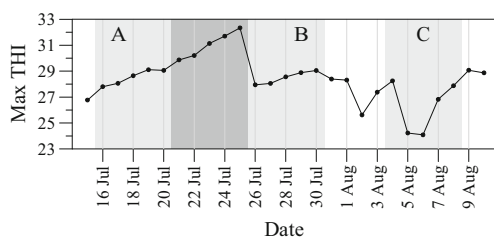
**Table 8** Descriptive statistics for the DMHVs of THI during HW and non-HW days

Value	HW days	Non-HW days
Maximum	32.3	30.1
90th percentile	31.1	29.1
50th percentile	30.3	28.0
10th percentile	29.9	26.6
Minimum	29.7	24.0

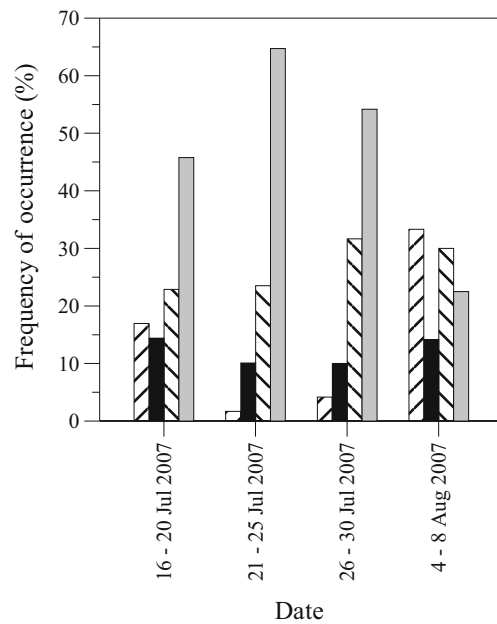
THI – hrs (Eq. 6) was utilized. In Eq. 6, THI is the hourly THI value and base is a certain heat-stress threshold. This index was introduced by Hahn and Mader (1997) as a measure of the magnitude of the daily heat load (intensity and duration) on dairy cows. The same index was also applied by Panagakis and Chronopoulou (2010) to describe the potential dairy ewes’ heat burden. They found that an increase of the Daily THI – hrs was related to elevated respiration rate and apparent short-term heat-stress.

$$\text{Daily THI-hrs} = \sum_{i=1}^{24} (\text{THI-base})_{\text{hr}=1, \dots, 24} \quad (6)$$

The Daily THI – hrs was applied for the four heat-stress categories presented in Table 2 during four 5-day periods in 2007: 16–20 July, 21–25 July, 26–30 July, and 4–8 August. The four periods were selected so as to study the magnitude of the heat load on sheep just before, during, and just after a significant HW event and during a period of relatively cool non-HW days. The variation of the DMHV of THI during the period 16 July 2007–10 August 2007 is presented in Fig. 4. During the period 21–25 July, all days were identified as HW days, while during the other three periods, non-HW day was identified. As it is already mentioned in this paper, a significant HW event could be regarded that occurred during the period 21–25 July (Fig. 4, bold grey area), as the two highest DMHVs of THI and temperature were observed during it. During the period 4–8 August (Fig. 4, light grey area C), which followed the significant HW event, the second and the third lowest DMHVs of THI and temperature were observed.



**Fig. 4** Variation of the DMHV of THI during the period 16 July 2007–10 August 2007. The four studied 5-day periods are highlighted (bold gray area: 21–25 July; light gray areas A, B, and C: 16–20 July, 26–30 July, and 4–8 August, respectively)



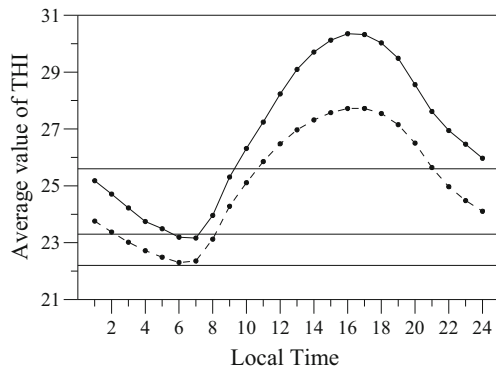
**Fig. 5** Frequency of occurrence of heat stress categories during the four studied 5-day periods (forward slashed bars: absence of heat stress; black bars: moderate heat stress; backward slashed bars: severe heat stress; grey bars: extreme severe heat stress)

Hourly THI values were exploited to calculate the frequency of occurrence of every heat-stress category during the four studied 5-day periods (Fig. 5). Figure 5 shows that small differences were detected between the frequency of occurrence of moderate heat-stress (0–4 %) and severe heat-stress (1–9 %) categories during the four periods. Heat-stress was absent in 17 % of the hours during the 5-day period just before the HW event. The corresponding percentage was reduced to 2 % during the HW event and remained also very low (i.e. 4 %) during the 5-day period just after the HW event. During the period 4–8 August 2007, sheep did not experience heat-stress during the 33 % of the hours. Regarding the frequency of occurrence of the extreme severe heat-stress category, the corresponding percentage during the HW event was 65 %, while it was decreased by 29, 16, and 65 % during the periods 16–20 July, 26–30 July, and 4–8 August, respectively.

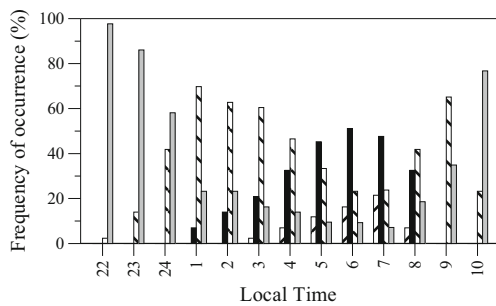
The Daily THI – hrs values for every heat-stress category during the four studied 5-day periods are presented in Table 9. During the HW event, the Daily THI – hrs value when sheep

**Table 9** Daily THI – hrs values for every heat stress category during the four studied 5-day periods

Period	Moderate heat stress	Severe heat stress	Extreme severe heat stress
16–20 July 2007	10.0	31.7	117.3
21–25 July 2007	5.2	32.8	243.7
26–30 July 2007	7.4	44.8	108.7
4–8 August 2007	12.4	31.4	35.5



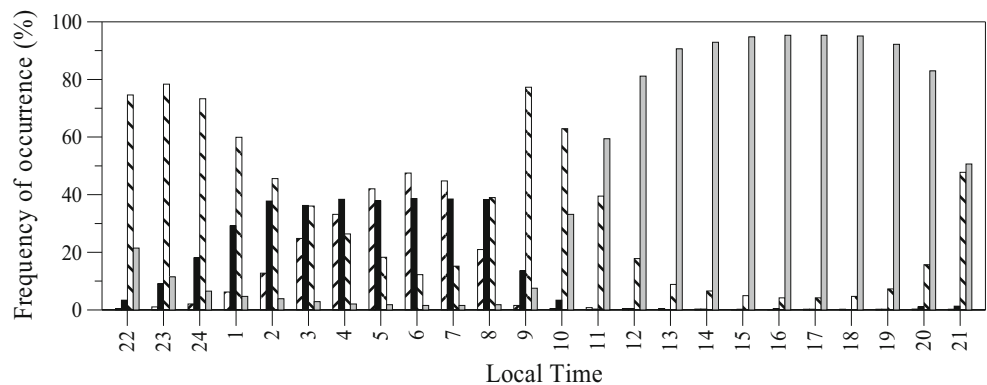
**Fig. 6** Averaged diurnal variation of THI during HW (solid line) and non-HW (dashed line) days. The horizontal solid lines correspond to THI thresholds (i.e. 22.2, 23.3, and 25.6)



**Fig. 7** Frequency of occurrence of every heat stress category per hour during HW days (bars as in Fig. 5)

experienced extreme severe heat-stress was 7.4 and 46.9 times higher than its value when sheep experienced severe and moderate heat-stress, respectively. The corresponding values for the periods 16–20 July, 26–30 July, and 4–8 August were 3.7 and 11.7, 2.4 and 14.6, and 1.1 and 2.9, respectively. Additionally, the Daily THI – hrs value when sheep experienced extreme severe heat-stress during the HW event was 243.7, while it was decreased by 52, 55, and 85 % during the periods 16–20 July, 26–30 July, and 4–8 August, respectively. These reductions are higher than the reductions reported in the previous paragraph regarding the frequency of occurrence of the extreme severe heat-stress category (i.e. 29, 16, and 65 %). These facts reveal

**Fig. 8** Frequency of occurrence of every heat stress category per hour during non-HW days (bars as in Fig. 5)



that THI levels during the HW event were much higher than during the other 5-day periods, supporting the conclusion that heat load on sheep was much higher during the HW event than during the other 5-day periods.

The averaged diurnal variation of THI during HW and non-HW days is presented in Fig. 6. Figure 6 shows that extreme severe heat-stress (THI  $\geq 25.6$ ) was observed between 1000 and 2400 hours local time during HW days, while during non-HW days, the corresponding time period was 1100–2100 hours local time. Additionally, Fig. 6 shows that the daily range of THI was higher during HW days than during non-HW days, being 7.2 and 5.4 °C, respectively. Moreover, Fig. 6 shows that peak THI levels were approximately 10 % higher during HW days than during non-HW days.

The diurnal variation of heat-stress levels was further studied by calculating the frequency of occurrence of every heat-stress category per hour during daytime and nighttime during HW and non-HW days (Figs. 7 and 8, respectively). Hours 1100–2100 are not included in Fig. 7 as during these hours during HW days, only extreme severe heat-stress was observed. During HW days (Fig. 7), extreme severe heat-stress became less important after midnight as heat-stress conditions were reduced. However, absence of heat-stress was observed only during hours 0300–0800, its higher frequency of occurrence being recorded at 0700 hours (i.e. 21 %). Heat-stress conditions per hour were better during non-HW days (Fig. 8), the improvement being more pronounced during nighttime. During daytime, extreme severe heat-stress conditions were observed during the vast majority of hours 1200–2000, while during nighttime, absence of heat-stress was observed during more than 21 % of the hours 0300–0800, its higher frequency of occurrence being recorded at 0600 (i.e. 48 %).

Silanikove (2000) stated that if the night temperature drops below 21 °C for 3–6 h, sheep have sufficient opportunity to lose all the heat gained from the previous day; therefore, the occurrence of such conditions was also investigated. During the night of HW days, the hourly temperature value never fell below 21 °C, while during the night of non-HW days, it fell below 21 °C for 49 h, a value that corresponds to 0.5 % of the total number of hours. These 49 h were distributed in 20 days,

and in 7 of them, the hourly temperature value was lower than 21 °C for three or more consecutive hours. Therefore, during HW days, sheep did not have the opportunity to dissipate the heat gained during the preceding day, while this opportunity was severely hampered during non-HW days.

## Conclusions

This paper presented a methodology to develop a long time series of temperature and relative humidity inside naturally ventilated sheep barns. Two linear regression models were developed that could also be applied to other sheep facilities located in the greater area, provided these facilities have similar characteristics regarding their structure and the animals housed. As continuous indoor measurements are not usually available for long periods, the application of this methodology provides a tool to assess summer sheep heat-stress levels for several years. In this paper, heat-stress levels were assessed during HW and non-HW days for a 7-year period and significant differences in THI levels were detected.

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