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ORIGINAL PAPER

Changes in the pattern of heat waves and the impacts on Holstein cows in a subtropical region

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Abstract
This study aimed to evaluate the change in the air temperature and the impacts of heat waves using Climate Change Indexes on the physiological and productive responses of lactating Holstein cows. Daily data of maximum and minimum air temperature for 1981–2021 were used. Heat waves were determined using six Climate Change Indexes. Individual data on respiratory rate, rectal temperature, and milk yield were collected in the summers of 2018, 2019, and 2021. The temperature trend analysis showed a significant ($p < 0.0001$) increase in maximum temperature, minimum temperature, and days in a heat wave. All six indexes increased significantly ($p > 0.01$). The increase in warm nights (> 20 °C) and the hottest days (> 35 °C) was the highest since 2010. Heat waves were classified into short (< 5 days) and long (> 5 days) of greater (> 36 °C) or lesser (< 36 °C) intensity. During the long and short heat waves of greater intensity, the respiratory rate increased ($p < 0.05$) until the fourth day. On the other hand, rectal temperature was higher ($p < 0.05$) from the fourth day until the end of the long heat waves. Therefore, the decrease in milk yield was significantly greater from the fourth or fifth day onwards. Finally, the evaluation method based on indexes was efficient to demonstrate the negative effects on physiological parameters and milk yield and can be indicated to evaluate heat stress in lactating cows.

Keywords Climate Change Indexes · Heat stress · Milk production · Rectal temperature · Respiration rate

Introduction

There is worldwide concern on the changes in global temperature patterns and climate projections. The sixth report by the Intergovernmental Panel on Climate Change (IPCC) highlights that, as early as 2030, the global average temperature should exceed 1.5 °C compared to pre-industrial levels (IPCC 2021). Most of Brazil is in the tropics and may be more susceptible to the increase in ambient temperature, ranging from 2 to 5 °C, by the end of the current century (IPCC 2021). Studies have shown the rise of heat waves (Russo et al. 2014; Guo et al. 2018). Brazil has been strongly affected by the increase in the frequency, duration, and intensity of heat waves in the last decade (Bitencourt et al. 2020; Costa et al. 2020).

The definitions of heat waves are broad and vary among studies (Perkins and Alexander 2013) and, therefore, no single method exists for their definition. Among the methods for evaluating heat waves, the 90th percentile method has been widely used and described, even in animal studies (Vitali et al. 2015; Guo et al. 2018; Costa et al. 2020). The use of heat wave indexes has stood out (Perkins and Alexander 2013), and the Climate Changes Indexes, developed by the Expert Team on Climate Change Detection and Indexes, can encompass different regions worldwide, being essential to understand the spatial extent and regional climate variability related to heat waves. These analyses use a climatic database comprising more than 30 years, being necessary to characterize the local climate pattern, considering the natural variability of climate (Bitencourt et al. 2020), and the impact of heat waves on animal production systems.

In tropical climates, Holstein cows are exposed to heat stress most of the year, increasing public concern about their welfare and reduced milk yield (Martello et al. 2010; Daltro

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et al. 2017; Santana et al. 2017; Mbuthia et al. 2021). The Holstein breed has been widely used to increase productivity on Brazilian dairy farms, including the traditional crossbreed Gyr × Holstein (da Costa et al. 2015). Thus, Holstein cows are presented in Brazil for many years; however, severe productive and reproductive losses are still observed when the cows experience heat stress (Baruselli et al. 2020). Studies have shown milk yield (MY) loss of 18 (Garcia et al. 2015) and 16% (Negri et al. 2021) in Brazilian Holstein cows that experienced heat stress. In addition, the last decade was the warmest on record (IPCC, 2021) and raises questions around Holstein cows' heat tolerance.

The prejudicial effects of thermal stress in dairy cows are widely studied by monitoring air temperature and several formulas of the temperature-humidity index (THI) (West 2003; Spiers et al. 2004; Rhoads et al. 2009). Although ambient temperature and THI are the most common methods, the use of climate data combined with the animals' physiological data is still scarce in studies addressing thermal stress. Thus, we suggest that daily data on minimum temperature (Tmin) and maximum temperature (Tmax) of the air and physiological variables indicative of thermal stress, such as respiratory rate (RR), rectal temperature (RT), and MY, can be evaluated according to heat wave indexes, broadening the understanding of thermoregulatory response of animals under a stressful environment. Several authors have studied the limit values of environmental temperature and physiological variables (particularly RR and RT) that reflect thermal stress or normothermia (Martello et al., 2010; da Costa et al. 2015; Daltro et al. 2017; Ferrazza et al. 2017; Pacheco et al. 2020), but this issue is unclear during heat waves.

Understanding how lactating Holstein cows respond to thermal stress through physiological and productive characteristics and how to identify adaptive responses during heat waves, in addition to the pattern of heat waves over the years, can support the development of strategies to mitigate the effect of extreme heat on animals and their production. In this context, this study hypothesized that the intensity and duration of heat waves alter physiological and productive responses in Holstein cows. For this purpose, the initial objective was (i) to study the change in air temperature pattern and to characterize heat waves through Climate Change Indexes and then (ii) to evaluate the effect of heat waves that occurred in the productive environment and the physiological and productive responses of Holstein cows in a subtropical environment.

Material and methods

Experimental procedures were approved by the Animal Ethics Committee (protocol 4,859,201,219) of the Faculty of Animal Science and Food Engineering following Brazilian Federal Regulation.

Study location

The municipality of Pirassununga is located at 21° 59′ 46″ S, 47° 25′ 33″ W, and 627 m above sea level, in the Southeastern region of Brazil. According to the Köppen-Geiger climate classification, the municipality has a Cwa climate, which is humid subtropical climate, with an average annual temperature ranging from 23.1 °C in summer to 16.9 °C in winter.

Climate data

In this study, two air temperature databases were used: the Prediction of Worldwide Energy Resources (NASA POWER) and Xavier et al. (2016). The first one was used to study, evaluate, and characterize the Tmin and Tmax pattern and days in heat waves (historical temperature series 1981–2021), and the second one (historical temperature series 1981–2013) was used to validate the data of the NASA POWER model, described below. Daily Tmin and Tmax data from the Pirassununga-SP region (1981–2021) were extracted from the NASA POWER database (available at: https://power.larc.nasa.gov). Such data offer two unique characteristics: they are global and continuous in time. The NASA POWER weather data was derived from the Modern-Era Retrospective Analysis for Research and Applications (MERRA-2) and GMAO Forward Processing-Instrument Teams (FP-IT) GEOS 5.12.4 model produced in near real-time. The data is provided in a global spatial resolution grid of 0.5° latitude/longitude, allowing analysis at regional-spatial scales (Marzouk 2021). The NASA POWER database demonstrated to reproduce weather data (Tmin and Tmax) satisfactorily for Brazilian territory (Monteiro et al. 2018). To validate the climate data from the NASA POWER model in the Pirassununga-SP region, daily data of Tmin and Tmax were downloaded and observed by Xavier et al. (2016) (1981–2013). Xavier et al. (2016) data are derived from observations of Brazilian weather stations interpolated to a regular grid with 0.25° horizontal resolution in latitude/longitude (available in: https://utexas.app.box.com/v/Xavier-etal-IJOC-DATA). Adequacy measures including the coefficient of determination (R^2) (Eq. 1), root-mean-square error (RMSE) (Eq. 2), normalized root-mean-square error (NRMSE) (Eq. 3), mean bias error (MBE) (Eq. 4), and Willmott's index of agreement (d) (Eq. 5) were used to evaluate the performance of the NASA POWER temperature data set compared to the observed data from Xavier et al. (2016).

$$R^2 = \frac{\left[\sum_{i=1}^{n}\left(P_i - \overline{P}\right)\left(O_i - \overline{O}\right)\right]^2}{\sum_{i=1}^{n}\left(P_i - \overline{P}\right)^{2}\sum_{i=1}^{n}\left(O_i - \overline{O}\right)^{2}} \tag{1}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(O_i - P_i\right)^2}{n}} \quad (2)$$

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\overline{O}} \quad (3)$$

$$\mathrm{MBE} = \frac{\sum_{i=1}^{n} (P_i - O_i)}{n} \quad (4)$$

$$d = \frac{1 - \left(\sum_{i=1}^{n} (O_i - P_i)\right)^2}{\sum_{i=1}^{n} \left(\left|P_i - \overline{O}\right| + \left|O_i - \overline{O}\right|\right)^2} 0 \leq d \leq 1 \quad (5)$$

where O_i is the observation value, P_i is the forecast value, $\bar{O}$ is the average observation value, and $\overline{P}$ is the average forecast value.

Temperature trend analyses

Mann–Kendall non-parametric method was used to study trends in Tmin and Tmax patterns and days in heat waves for the 1981–2021 historical series, based on the NASA POWER model. This method is indicated to analyze trends in climatological time series, as it is robust and sequential, does not require normal data distribution, and is little influenced by abrupt changes or non-homogeneous series (Salviano et al. 2016). The Kendall τ (tau) correlation coefficient was determined (Costa et al. 2020), which is an association measure for ordinal variables not influenced by variance or outliers. Then, Pettitt's test was used to verify the change point in the 1981–2021 series homogeneity. Pettitt's test is a non-parametric test that uses the Mann–Whitney statistic, which verifies if two samples, $\times 1, \ldots, xt$ and $x, t + 1, \ldots, xN$, are part of the same population or not. The data were evaluated using the R software.

Heat wave indexes

The RClimDex software was used to calculate and indicate the heat wave indexes using a bootstrap approach proposed by Zhang and Yang (2004). Heat wave events for the 1981–2021 data series were determined based on the analysis of the daily data of minimum and maximum ambient temperature, as shown in Table 1. In total, six Climate Change Indexes were used, developed by the Expert Team on Climate Change Detection and Indexes (ETCCDI) (http://etccdi.pacificclimate.org/list_27_indices.shtml). Through RClimDex, it is possible to identify the slope and the significance of the linear regressions, which were considered possible change in the pattern of heat waves when statistically significant ($p < 0.05$).

Cow data

Data on the RR, RT, and MY of cows were obtained from the dairy herd of the Faculty of Animal Science and Food Engineering (FZEA) of the University of São Paulo, Pirassununga, São Paulo, during the summers of 2018, 2019, and 2021 (Table 2). Healthy primiparous and multiparous lactating Holstein cows, without history of clinical mastitis, lameness, dried with 60 days in the last lactation, with normal calving and fecundated (156.1 ± 114.4 days in milk), were housed in a free-stall system equipped with 24-h connected fans. Feeding and milking were performed twice a day, at 7 a.m. and 3 p.m. The MY was automatically recorded once daily by the DeLaval InService™ system. The herd has MY capacity of 21.3 kg/cow. Cows' diet consisted of corn silage (30%), Tifton 85 hay (10%), and concentrate (60%), containing 76% total digestible nutrients and 18% crude protein. The diet was offered with 20% feed bunk refusal. RR, RT, and MY were collected during 70 days (20 days of 2018, 20 days of 2019, and 30 days of 2021) at 5 a.m., 1 p.m., and 7 p.m. The RT was manually recorded with a digital thermometer (VMDT01, VioMed, China). The RR was determined by counting the time for every ten flank movements, and the

Table 1 Climate Change Indexes used for the analysis of daily data of maximum (Tmax) and minimum (Tmin) temperature with definition and units in the 1981–2020 series

Index	Name	Definition	Unit
SU	Summer days	Annual count of days when Tmax > 25 °C	Days
TR	Tropical night	Annual count of days when Tmin > 20 °C	Days
TX90P	Warm days	Percentage of days when Tmax > 90th percentile. TX90P be the calendar day 90th percentile centered on a 5-day window	% days
TN90P	Warm nights	Percentage of days when Tmin > 90th percentile for Tmin. TN90P be the calendar day 90th percentile centered on a 5-day window	% days
TX35	Hottest days	The limit is fixed at 35 °C for Tmax	Days
WSDI	Warm spell duration index	Annual count of days with at least 6 consecutive days when Tmax > 90th percentile	Days

Table 2 Descriptive statistics for days in milking (DIM), age, parity, and milk yield from the dairy cow database

Item	Year	Mean ± SD
DIM (days)	2018	242.80 ± 90.28
	2019	361.95 ± 129.57
	2021	216.02 ± 179.11
Age (month)	2018	53.00 ± 16.34
	2019	63.22 ± 17.41
	2021	49.10 ± 18.93
Parity (number)	2018	2.37 ± 1.0
	2019	2.37 ± 1.0
	2021	2.29 ± 1.4
Milk yield (kg)	2018	21.50 ± 6.61
	2019	15.93 ± 4.01
	2021	20.36 ± 6.26

number of movements per minute was calculated. Thus, it composed an initial database with 5883 data. The days in milk (DIM) were divided into seven classes defined as 1 (1 to 30), 2 (31 to 60), 3 (61 to 90), 4 (91 to 120), 5 (121 to 180), 6 (181 to 300), and 7 (> 301). Cows were also categorized by parity as first, second, and third or more calving. Cows with missing data or failures were removed. In the end, 4048 RR and RT data from 52 cows were analyzed.

Statistical analysis

In evaluating heat wave indexes in 2018, 2019, and 2021, during which physiological data were collected, the occurrence of TX90P and TX35 indexes was identified (Table 1). The relationship between RR and RT data with the indexes was investigated using the MIXED procedure of SAS (version 9.4; SAS Institute Inc., Cary, NC). All animal's variables and their interactions were included in the initial model to fit the best representation of RR and RT responses during heat waves. Only variables with $p < 0.05$ were included in the final model after a manual selection. According to the Bayesian information criterion (BIC), the composite symmetry structure (CS) was the best among all the error structures investigated. The final model used to describe the relationship between RR and RT responses with TX90P and TX35 indexes was:

$$\begin{aligned} Y_{\mathrm{ijklmno}} = {} & \mathrm{HWC_i} + \mathrm{day_j} + \mathrm{DIM_k} + \mathrm{lact_l} + \mathrm{HWC_i} \times \mathrm{day_j} \\ & + \mathrm{HWC_i} \times \mathrm{DIM_k} + \mathrm{HWC_i} \times \mathrm{lact_l} \\ & + \mathrm{Calving_{year}}(\mathrm{calving_{month}})_m + \mathrm{cow\ (hour)}_n \\ & + \mathrm{cow\ (year} \times \mathrm{calving_{month}} \times \mathrm{calving_{year}} \times \mathrm{lact_l})_o + e_{\mathrm{ijklmno}} \end{aligned} \tag{6}$$

where Y_{ijklmno} is RR or RT; $\mathrm{HWC_i}$ is the fixed effect of TX90P or TX35 heat wave index; $\mathrm{day_j}$ is the fixed effect of heat wave duration within the TX90P or TX35 index; $\mathrm{DIM_k}$ is the fixed effect of DIM classes; $\mathrm{lact_l}$ is the fixed effect of parity classes; $\mathrm{HWC_i} \times \mathrm{day_j}$, $\mathrm{HWC_i} \times \mathrm{DIM_k}$, and $\mathrm{HWC_i} \times \mathrm{lact_l}$ are the fixed effects of interaction; $\mathrm{Calving_{year}}(\mathrm{calving_{month}})_m$ is the random effect of the year of calving nested to the month of calving; cow $(\mathrm{hour})_n$ is the random effect of the cow nested at the time of collection (5 a.m., 1 p.m., and 7 p.m.); cow $(\mathrm{year} \times \mathrm{calving_{month}} \times \mathrm{calving_{year}} \times \mathrm{lact_l})_o$ is the random effect of the cow nested to the interactions between year (2018, 2019, and 2021), month of calving, year of calving, and parity class; and e_{ijklmno} is the random residual effect. The residues were tested for normality. The means of the least squares were estimated for the days in the heat wave index, TX90P or TX35, and the differences were tested in LSMEANS considering significant $p < 0.05$.

The relationship between the decrease in MY and the heat waves identified with the TX90P or TX35 indexes was tested using the GLIMMIX procedure of the SAS (version 9.4). The daily MY loss per cow was calculated based on the equation (Milk loss = Milk yield at the test day − Milk yield the previous day). Similar to Eq. 6 and statistical estimators, the final model to verify the decrease in MY was:

$$\begin{aligned} Y_{\mathrm{ijklm}} = {} & \mathrm{day_i} + \mathrm{DIM_j} + \mathrm{lact_k} + \mathrm{day_i} \times \mathrm{DIM_j} + \mathrm{day_i} \times \mathrm{lact_k} + \mathrm{Calving_{year}} \\ & (\mathrm{calving_{month}})_l + \mathrm{cow\ (year} \times \mathrm{calving_{month}} \times \mathrm{calving_{year}} \times \mathrm{lact_k})_m + e_{\mathrm{ijklm}} \end{aligned} \tag{7}$$

where Y_{ijklm} represents the decrease in MY and the other variables are described in Eq. 6.

Results

Analysis of change in air temperature pattern and characterization of heat waves

The NASA POWER model had a good performance compared to the meteorological data from Xavier et al. (2016). Table 3 shows the adequacy measures of R^2, RMSE, NRMSE, MBE, and Willmott's index of agreement. The results show that the NASA POWER model represented Tmin and Tmax data from the study location. Although Tmax presented errors slightly higher than Tmin (RMSE = 2.27 and $R^2 = 0.60$), the bias was low (0.27), and the index of agreement "*d*" was 0.87, indicating that the model represented the behavior and seasonality of the ambient temperature in the studied area. Due to this similarity between the ambient temperature data of Xavier et al. (2016) and NASA POWER, it was possible to use the NASA POWER model for the analysis of this investigation. When analyzing Tmin and Tmax series, we observed a significant increase, with a positive trend in the historical series 1981–2021 (Table 4). Pettitt's test confirmed the change point when the Tmax and Tmin average increased series on the annual and seasonal scales (when considering

Table 3 Coefficient of determination (R^2), root-mean-square error (RMSE), normalized root-mean-square error (NRMSE), mean bias (Bias), and index of agreement (d) between the NASA POWER data versus the observed weather data (Xavier et al. 2016) for minimum and maximum temperatures

Measure[1]	Tmax	Tmin
R^2	0.60	0.86
RMSE	2.27	1.35
NRMSE	0.08	0.09
Bias	0.27	0.26
d	0.87	0.96

[1]The maximum and minimum temperature data were evaluated in the 1981–2013 series for Xavier et al. (2016) and NASA POWER

the seasons). The maximum and minimum temperature's average was significantly higher after the change point detected by the Pettit test, except for autumn Tmin. The largest increases observed were in Tmax of the winter (1.9 °C) and spring (2.8 °C) and Tmin of the winter (1.0 °C) and spring (0.8 °C) (Table 4). The number of days in heat waves also increased significantly in the 1981–2021 series (Fig. 1 and Table 4). All heat wave indexes indicated an increasing curve ($p < 0.05$) from 1981 to 2021 (Fig. 1). The TX90P and TN90P indexes showed significant increasing trends in the number of hottest days and nights in the 1981–2021 series, also observed for the TR20, TX35, and WSDI indexes (Fig. 1). The SU index showed that about 98.6% (300 days) of the year had Tmax above the threshold of 25 °C.

Physiological and productive responses during heat waves

The evaluation of physiological and productive responses of cows subjected to heat waves was characterized by TX90P and TX35 indexes, and they were classified according to their duration and intensity: short duration (up to 5 days); long duration (longer than 5 days); higher intensity (Tmax > 36 °C); and lower intensity (Tmax < 36 °C). The statistical estimators for the models used to describe the relationship between respiratory rate and rectal temperature and decrease in MY with TX90P and TX35 are described in Table 5. We observed that when cows experienced short-duration and high-intensity heat waves characterized by the TX90P index, RR and RT responses were elevated ($p < 0.01$) for moderate and severe heat stress levels (Fig. 2a). Also, significant loss in MY ($p > 0.01$) was observed on the 1st day and at 48 h after the end of the heat wave (Fig. 2b).

Table 4 Mann–Kendall and Pettit trend analyses for the minimum (Tmin) and maximum (Tmax) temperature and days of heat waves by annual and season (summer, autumn, winter, and spring) in the NASA POWER data series (1981–2020)

Parameter	Kendall's test			Pettit test[2]			
	Tau	p-value	Trend analysis	Before	After	Year change point	p-value
Annual							
Tmin	0.07	< .0001	Positive	15.8[b]	16.5[a]	1997	< .0001
Tmax	0.12	< .0001	Positive	27.2[b]	28.4[a]	1997	< .0001
Days in heat waves[1]	0.44	< .0001	Positive	-	-	-	-
Summer							
Tmin	0.16	< .0001	Positive	18.8[b]	19.3[a]	2005	< .0001
Tmax	0.13	< .0001	Positive	27.5[b]	28.8[a]	2012	< .0001
Days in heat waves[1]	0.38	< .0001	Positive	-	-	-	-
Autumn							
Tmin	0.02	0.10	*Without*	14.9[a]	14.8[a]	-	0.18
Tmax	0.14	< .0001	Positive	25.3[b]	26.4[a]	2000	< .0001
Days in heat waves[1]	0.43	< .0001	Positive	-	-		-
Winter							
Tmin	0.15	< .0001	Positive	12.6[b]	13.6[a]	1997	< .0001
Tmax	0.16	< .0001	Positive	26.8[b]	28.7[a]	1997	< .0001
Days in heat waves[1]	0.39	< .0001	Positive	-	-	-	-
Spring							
Tmin	0.13	< .0001	Positive	17.5[b]	18.3[a]	2001	< .0001
Tmax	0.08	< .0001	Positive	27.4[b]	30.2[a]	1984	< .0001
Days in heat waves[1]	0.20	0.07	*Without*	-	-	-	-

[1]Number of days when Tmax > 90th percentile (TX90P) centered on a 5-day window

[2]The change point in homogeneity of Tmin and Tmax

[a,b]Means within a row with different superscripts differ ($p \leq 0.05$)

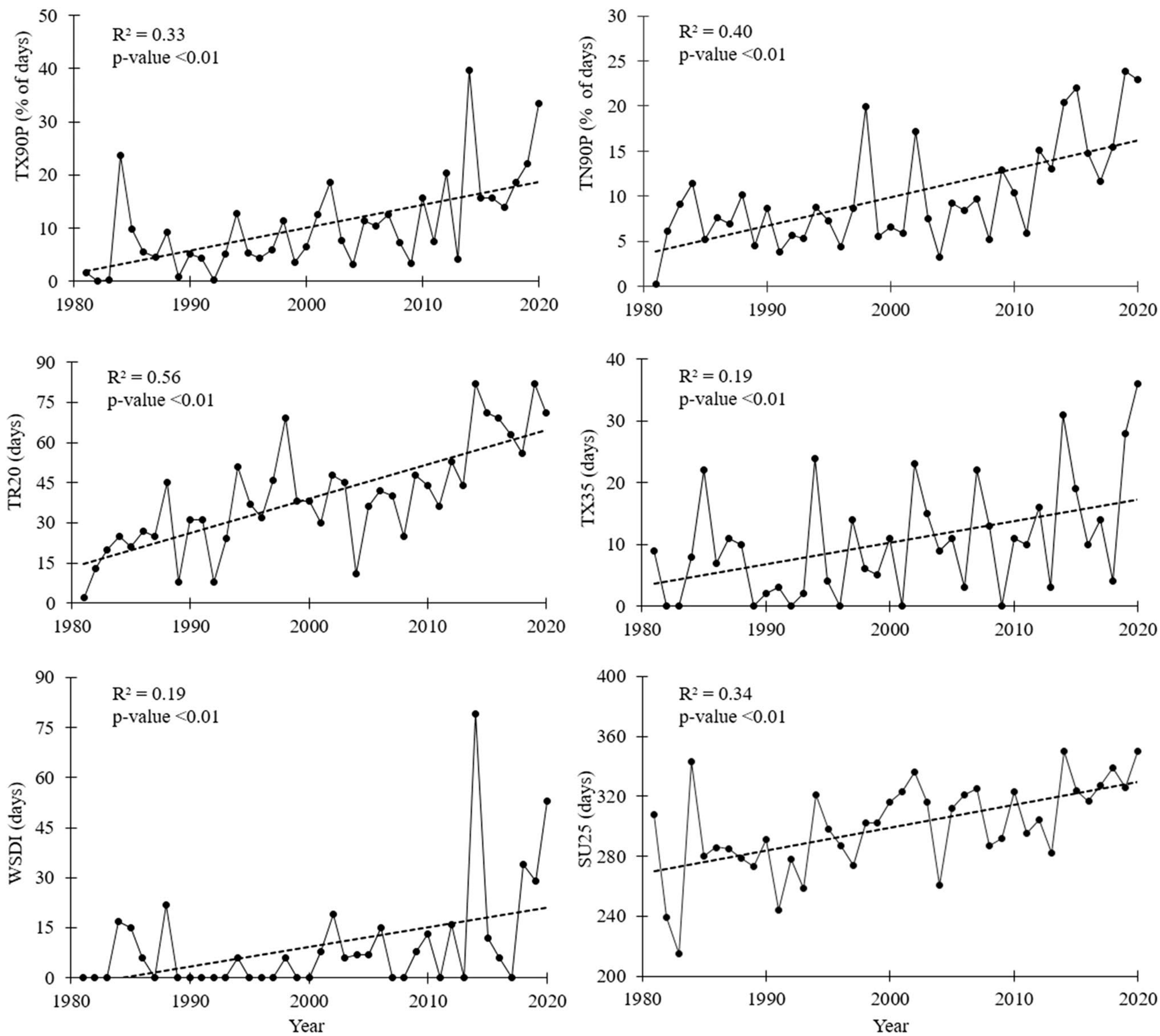


Fig. 1 Linear regression of the Climate Change Indexes to accompany their moderated evolution of the changes in climate within the NASA POWER data series 1981–2021

Table 5 Statistical estimators of coefficient of determination (R^2), variance (S), and coefficient of variation (CV) for the fitted models used to describe the relationship between respiratory rate, rectal temperature, and milk yield loss during TX90P and TX35 indexes

Item	TX90P			TX35		
	R^2	S	CV (%)	R^2	S	CV (%)
Respiratory rate (mov/min^{-1})	0.62	11.40	25.40	0.54	12.10	23.80
Rectal temperature (°C)	0.75	0.37	1.85	0.70	0.39	1.80
Milk yield loss (kg/day^{-1})	0.79	2.50	27.60	0.86	2.04	28.50

On the other hand, short and low-intensity heat waves were not enough to change RR and RT ($p > 0.05$) but caused a decrease in MY ($p < 0.01$) (Fig. 2f). During a short duration and lower intensity heat wave characterized by the TX35 index (Fig. 3a and c), RR slightly oscillated during the heat wave, whereas RT was higher ($p < 0.01$) only on the 4th day

(Fig. 3c), compared to the previous ones. Small reductions in MY were observed (Fig. 3b and d). During a long duration and higher intensity heat wave in the TX90P and TX35 index (Figs. 2g and 3e), in which Tmax was greater than 36 °C, RR gradually increased until the 4th day (Fig. 2g). RT was higher ($p < 0.01$) from the 3rd to 5th day, increasing to hyperthermia on the 6th day (Fig. 2g). The MY decrease ($p < 0.01$) occurred from the 5th day up to 48 h after the heat wave (Fig. 2h). Another long duration and higher intensity heat wave in the TX35 index (Fig. 3g) caused physiologic adaptive response from the 6th day, with decrease in the RR and RT ($p < 0.01$). Also, the Tmax decreased from the 6th day but remained above 36 °C (Fig. 3g) and a drop in MY was observed from the 4th day onwards.

Discussion

One of the limiting factors in dairy industry is the environment, a crucial aspect when studying heat stress in tropical and subtropical climates (da Costa et al. 2015). In Brazil, informational data on dairy farms are lacking due to territorial extension for reasons of territorial extension (Parente et al. 2019), management systems (Tramontini et al. 2021), breeds and breeding herds (da Costa et al. 2015), and climatic diversity (Marinho et al. 2020). Considering the heterogeneity of the dairy farms and climate, regional studies must be carried out so that action proposals can be better oriented.

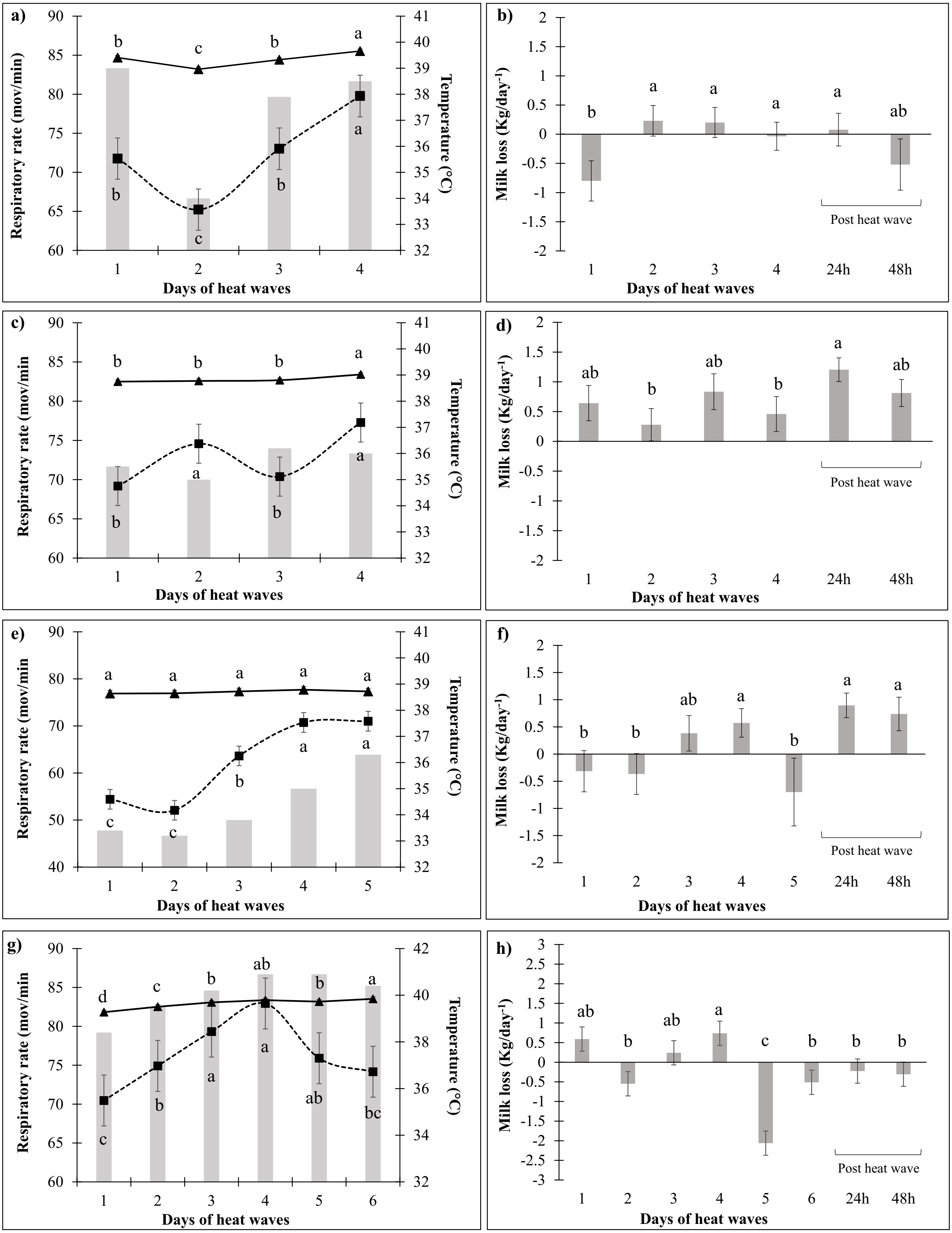
In this study, the first objective was to evaluate the change in the air temperature pattern and characterize heat waves through Climate Change Indexes. In this sense, it was observed an increase in Tmax and Tmin for the study region from 1981 to 2021. As a result, we found a significant increase trend in the incidence of extreme heat events and more frequent, longer, and intense heat waves since 2010. The results showed that about 88.1% of the days of 2010–2020 exceeded 25 °C by SU25 index, an increase of 14% compared to the 1981–2000 period. Still, in the 2018, 2019, and 2020, it presented 93, 89, and 96% of days above 25 °C. This ambient temperature of 25 °C is considered the upper limit for heat stress in Holstein cows (Berman et al. 1985). Throughout the months of the year, dairy cows adapt to climate variability and undergo a process of acclimatization and adaptation to the hot climate (Collier et al. 2019). However, although Brazilian Holstein cows are acclimatized to tropical and subtropical climates, some authors indicate that these animals have poor heat tolerance and losses in milk production are recurrent (Santana et al. 2016, 2017; Negri et al. 2021).

The number of days in the year in heat wave, based on the TX35 index, increased by 60% in the 2010s, compared to the 2000s. Also, it was observed that the percentage of days in heat waves indicated by the TX90P index increased by 92% and the TR20 index indicated that the number of warm nights increased by 69%. The increase in warm nights (> 20 °C) is a problem for dairy farms, making it difficult for animals to dissipate heat (Vitali et al. 2015). During hot days, the nighttime is crucial for cows to recover thermal balance and not harm their health, welfare, and performance (da Costa et al. 2015; Avendaño-Reyes et al. 2021; Mbuthia et al. 2021). These results corroborate the observations of the IPCC (2021) considering the accelerated changes in temperature patterns of the last decade, causing a global concern on the resilience of dairy production systems and the impacts on animal performance and productivity in a future warmer climate (Fodor et al. 2018).

Brazil has been affected by the increase in the number and severity of heat waves (Bitencourt et al. 2020; Costa et al. 2020). Thus, analyzing the behavior of environmental temperature in a series of data in different producing regions is essential to plan and assist in management strategies that seek to minimize the negative effects of the thermal environment. Various THI indexes have been used to characterize the thermal and humidity conditions in the cowshed, but according to Dikmen and Hansen (2009), it is not suitable for subtropical climate environments. In the present study, we demonstrated that during the occurrence of heat waves (TX90P and TX35 indexes), the daily Tmax of 36 °C was a threshold to cause physiological changes in Holstein cows.

In the first 4 days of long duration heat waves, a significant increase in response to heat stress was observed, such as the elevation of RR (> 80 mov/min), so when Tmax continued to increase from the 4th day (> 36 °C), the cows were no longer able to dissipate heat only by breathing, with an inverse response to TR. Then, RT increased due to hyperthermia from the 5th day. RT follows a daily circadian rhythm, being lower in the early morning and higher in the late afternoon (Martello et al. 2010); consequently, the highest environmental Tmin and Tmax during heat waves (especially in the afternoon) cause a significant increase in nighttime body temperature. These study results are significant due to its essential information (with RR and RT) on the adaptation of Brazilian Holstein cows exposed to extreme heat load. It is important to emphasize that for countries with a hot climate, a breeding program for high-yielding and heat-tolerant cows must consider the RR and RT information. Additionally, we also emphasize that, unlike most studies, this study used empirical data collected in the farm during heat wave events, hampering the comparison between our results and other studies performed in climate chambers.

In this study, long duration heat waves caused the greatest decline in MY in 24 to 48 h after RR and RT reached the highest values. Thus, the greatest decreases in MY were observed from the 5th day when MY was not recovered until the end of the heat wave. In this case, cows spent less


a)
Respiratory rate (mov/min)
Temperature (°C)
Days of heat waves
b)
Milk loss (Kg/day-1)
Post heat wave
Days of heat waves
1 2 3 4 24h 48h
c)
Respiratory rate (mov/min
Temperature (°C)
Days of heat waves
d)
Milk loss (Kg/day-1)
Post heat wave
Days of heat waves
e)
Respiratory rate (mov/min
Temperature (°C)
Days of heat waves
f)
Milk loss (Kg/day-1)
Post heat wave
Days of heat waves
g)
Respiratory rate (mov/min
Temperature (°C)
Days of heat waves
h)
Milk loss (Kg/day-1)
Post heat wave
Days of heat waves

◂**Fig. 2** Least squares estimates for respiratory rate (dotted line), rectal temperature (solid line), milk loss (dark gray bars), and the daily maximum temperature (gray bars) during short (a, b, c, d, e, and f) and long (g and h) heat waves calculated by the TX90P index. Data are presented as mean ± standard error of the mean. Means within a row with different superscripts differ ($p \leq 0.05$)

time feeding in an attempt to restore thermal equilibrium (West 2003; Spiers et al. 2004; Rhoads et al. 2009). Furthermore, the high physiological cost for adaptive process seems to have caused a drop in MY of − 1.33 (Fig. 3h) and − 2.00 kg/cow (Figs. 2h and 3f). Other studies also detected a drop in MY from 0.25 to 4.62 kg/day during heat stress of Brazilian Holstein cows, but did not assess MY considering periods of heat waves (Santana et al. 2017; Negri et al. 2021). To our knowledge, there are no records on the effects of thermal stress in lactating Holstein cows submitted to heat waves by the subtropical climate. On the other hand, short duration (up to 5 days) was observed and less intense heat waves did not cause a significant decrease in MY. In contrast, Garner et al. (2017) observed in a 4-day simulated heat wave (maximum temperature of 33 °C) similar RR and RT values to ours, and reductions in MY continued up to 4–5 days after the end of the heat wave.

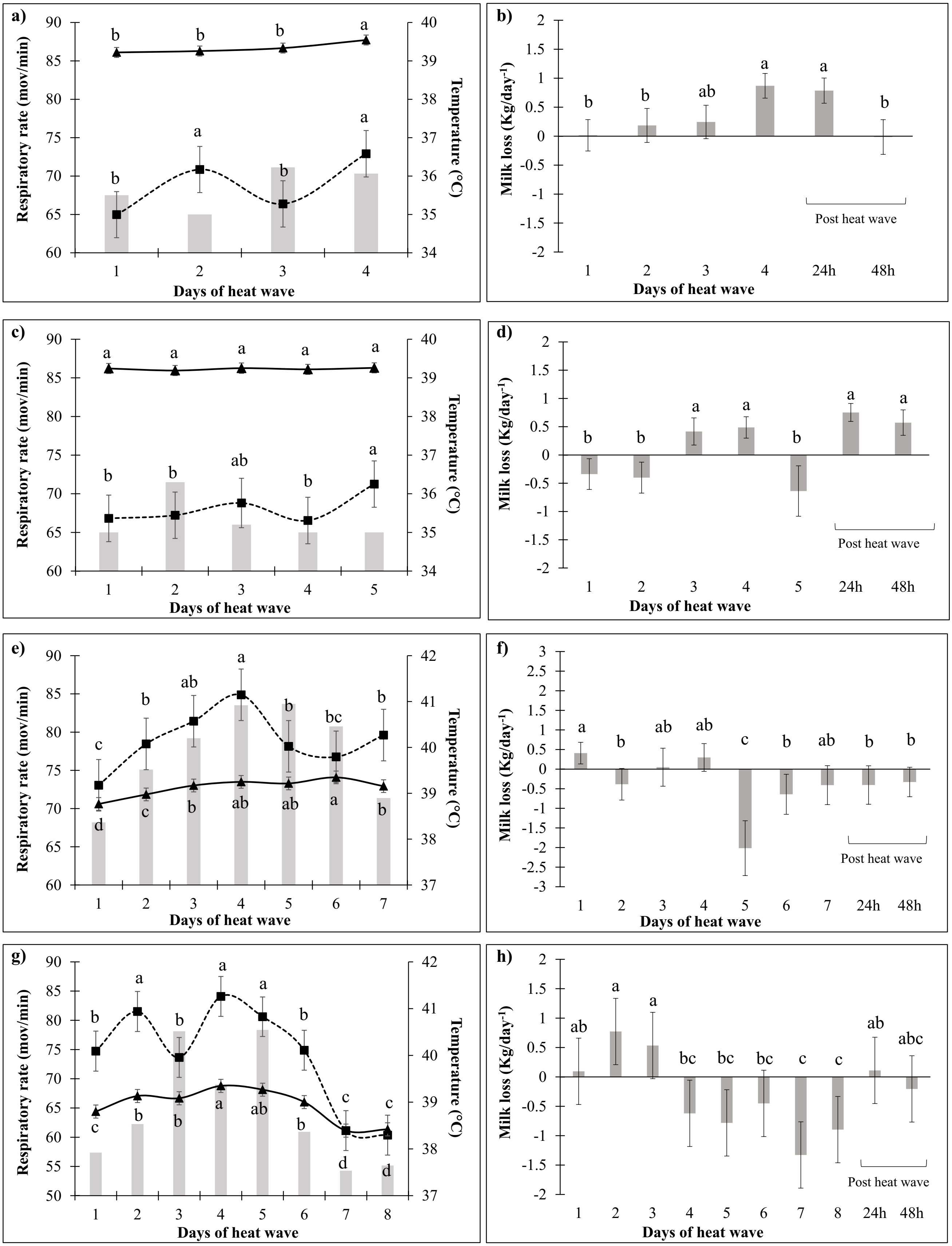
In a long heat wave of 8 days (Fig. 3g), RR and RT increased significantly for thermal stress levels, with daily Tmax reaching 40.5 °C on the 3rd and 5th day. However, after the 5th day, it may have occurred adaptive responses in cows, since a significant reduction in RR and RT was observed from day 6 for thermal comfort levels, even with Tmax > 36 °C. Additionally, in this same environment, MY began to decrease from the 4th day, and the largest decreases in MY were observed at days 7 and 8, raising again the MY only after 48 h later of the heat wave. This result suggests that the magnitude of the heat waves was an important factor in the process of adaptation to heat of Holstein cows. It is interesting that single days of extreme heat or short heat waves were not enough to cause thermal discomfort in cows. Vitali et al. (2015) found high mortality of Italian Holstein cows (temperate climate) with only 3 days of heat wave. Thus, our results reinforce that Holstein cows in subtropical climates have undergone an acclimatization process over the years, but that it is still insufficient to maintain high production during severe heat waves. Therefore, the duration and intensity of the heat wave are an important aspect and should be considered in the evaluation of thermal stress in dairy cows in a tropical and subtropical climate. Means to mitigate thermal stress in dairy cows are urgent and necessary.

A common strategy to minimize the negative effects of heat stress on lactating cows is to employ housing ventilation systems (Spiers et al. 2018) which could reduce the impact of the magnitude of heat waves on Holstein cows. In the present study, cows had artificial ventilation for 24 h during the heat waves, which was insufficient to maintain thermal balance, demonstrating that excess heat is not a simple problem to solve. Other authors also demonstrated that ventilation by sprinklers and fans was insufficient to maintain thermoregulation and milk production during high temperatures in subtropical climate (Santana et al. 2016; Dikmen et al. 2020). Our objective was not to evaluate ventilation methodologies; however, the ventilated environment may have favored animal thermal comfort during short-term heat waves. On the other hand, the long heat waves had negative impacts on the RR, RT, and MY. High-temperature adaptation management systems and options, which are recurrent already in current climate scenarios (as demonstrated in this study), and in future climate change scenarios (Fodor et al. 2018; IPCC, 2021), should be rethought, evaluating the system as a whole, in a regional or local scope, according to the conditions of the dairy farmer (Claessens et al. 2012; Harrison et al. 2017) and not treated generically (Kalaugher et al. 2017). Despite the efforts to employ relief mechanisms to diminish thermal stress, productive and reproductive losses in dairy cows are still frequent during extreme heat (Baruselli et al. 2020; Avendaño-Reyes et al. 2021; Mbuthia et al. 2021).

Generally, this study demonstrated that Holstein cows experienced intense thermal stress during long heat waves (> 5 days) in the study location. The evaluation method based on daily Tmax and heat wave indexes, from the model data (NASA POWER), was efficient to demonstrate the negative effects on physiological parameters and MY. This method is a new approach that can help farmers, public management, and dairy systems to seek new ways to improve animal management.

Conclusion

These results confirm the increase in the maximum and minimum daily temperature in the 1981–2021 series in the study site, with a significant increase in the number and intensity of heat waves in the last decade (2010–2020). We identified the greatest impact on respiratory rate and rectal temperature of Holstein cows during long-lasting and more intense heat waves; however, there was a threshold of 36 °C of air temperature to achieve severe thermal stress and adaptive responses. Heat waves decreased daily milk yield when respiration rate and rectal temperature also reached the highest values, with no MY recovery after 5 days during long-lasting heat waves.


a)
Respiratory rate (mov/min)
Temperature (°C)
Days of heat wave
b)
Milk loss (Kg/day-1)
Post heat wave
Days of heat wave
24h
48h
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Respiratory rate (mov/min)
Temperature (°C)
Days of heat wave
d)
Milk loss (Kg/day-1)
Post heat wave
Days of heat wave
24h
48h
e)
Respiratory rate (mov/min)
Temperature (°C)
Days of heat wave
f)
Milk loss (Kg/day-1)
Post heat wave
Days of heat wave
24h
48h
g)
Respiratory rate (mov/min)
Temperature (°C)
Days of heat wave
h)
Milk loss (Kg/day-1)
Post heat wave
Days of heat wave
24h
48h

◂**Fig. 3** Least squares estimates for respiratory rate (dotted line), rectal temperature (solid line), milk loss (dark gray bars), and the daily maximum temperature (gray bars) during short (a, b, c, and d) and long (e, f, g, and h) heat waves calculated by the TX35 index. Data are presented as mean ± standard error of the mean. Means within a row with different superscripts differ ($p \leq 0.05$)

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Declarations

Ethics approval All procedures performed in studies involving animals were in accordance with the current Federal Law n° 11.794, sanctioned by the President of the Republic on November 8, 2008. The law is available in full at http://planalto.gov.br/ccivil_03/_Ato2007-2010/2008/Lei/L11794.htm and is known as Arouca Law, which regulates the scientific use of animals in Brazil. The Ethic Committee on Animal Use of the School of Animal Science and Food Engineering of São Paulo University protocol number CEUA 4859201219 approved the experimental procedures.

Conflict of interest The authors declare no competing interests.

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