International Journal of Biometeorology (2023) 67:1273–1277
https://doi.org/10.1007/s00484-023-02493-5

SHORT COMMUNICATION

NASA POWER satellite meteorological system is a good tool for obtaining estimates of the temperature-humidity index under Brazilian conditions compared to INMET weather stations data

Eula Regina Carrara[1] · Paulo Sávio Lopes[1] · Arícia Chaves Zanetti Reis[1] · Jéssica Xavier Silva[1] · Layla Cristien de Cassia Miranda Dias[1] · Érica Beatriz Schultz[1] · Daniele Botelho Diniz Marques[1] · Delvan Alves da Silva[1] · Renata Veroneze[1] · Ricardo Guimarães Andrade[2] · Maria Gabriela Campolina Diniz Peixoto[2]

Received: 7 April 2023 / Revised: 2 May 2023 / Accepted: 11 May 2023 / Published online: 16 May 2023

Abstract

Heat stress negatively affects livestock, with undesirable effects on animals' production and reproduction. Temperature and humidity index (THI) is a climatic variable used worldwide to study the effect of heat stress on farm animals. Temperature and humidity data can be obtained in Brazil through the National Institute of Meteorology (INMET), but complete data may not be available due to temporary failures on weather stations. An alternative to obtaining meteorological data is the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) satellite-based weather system. We aimed to compare THI estimates obtained from INMET weather stations and NASA POWER meteorological information sources using Pearson correlation and linear regression. After quality check, data from 489 INMET weather stations were used. The hourly, average daily and maximum daily THI were evaluated. We found greater correlations and better regression evaluation metrics when average daily THI values were considered, followed by maximum daily THI, and hourly THI. NASA POWER satellite-based weather system is a suitable tool for obtaining the average and maximum THI values using information collected from Brazil, showing high correlations with THI estimates from INMET and good regression evaluation metrics, and can assist studies that aim to analyze the impact of heat stress on livestock production in Brazil, providing additional data to complement the existing information available in the INMET database.

Keywords Köppen classification · Heat stress · Linear regression · Pearson correlation · THI · Tropical climate

Introduction

Brazil is one of the largest producers and exporters of animal products in the world (USDA 2023), standing out in the global food trade (Ferraz and Felício 2010). Livestock production in Brazil and in the world is highly affected by climatic conditions. If greenhouse gas emissions are not curbed in the coming years, Brazil may expect a general temperature rise exceeding 1.5 °C by 2030 (IPCC 2021). In this sense, animal responses to these climatic changes, as heat stress, may cause serious physiological changes, along with negative effects on animals' production and reproduction (West 2003; Renaudeau et al. 2012). In studies on heat stress in livestock, the temperature and humidity index (THI), usually calculated using daily temperature and humidity data from weather station databases, is mostly used as a climatic indicator.

In Brazil, the National Institute of Meteorology (INMET) offers the possibility of immediate download of meteorological information from the year 2000 onwards at https://bdmep.inmet.gov.br. Several studies have used information from the INMET database to evaluate the effects of heat stress on livestock in Brazil (Santana et al. 2016, 2020; Cordeiro et al. 2020; Negri et al. 2021; Stefani et al. 2022). Unfortunately, the weather coverage is sparse in some regions and complete information is not always available for a given day or time period, since weather stations may have power outages. For example, between 2020 and 2022,

✉ Eula Regina Carrara
eulacarrara@gmail.com

[1] Department of Animal Science, Federal University of Viçosa, Viçosa, MG, Brazil

[2] Embrapa Dairy Cattle, Juiz de Fora, MG, Brazil

around 20% of the stations experienced a power outage, and up to 42% had a blackout in April 2021, a negative impact of the COVID-19 pandemic (INMET 2022). Moreover, the properties that have production animals are not always located near INMET weather stations, which can reduce the precision of THI estimates for these locations.

An alternative to obtaining meteorological data is the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) satellite-based weather system. Data can be downloaded from https://power.larc.nasa.gov by entering the latitude and longitude of the desired location, with single point, regional, or global coverage, and can be exported to a user-friendly output (e.g., in ASCII format). Recent studies have used meteorological data from the NASA POWER project to calculate THI and assess the effects of heat stress on livestock (Carrara et al. 2021; Manica et al. 2022; Salvian et al. 2022; Dauria et al. 2022; Rockett et al. 2023).

However, Brazil has a great climatic diversity and the production animals, mainly cattle, are mostly pasture-raised. In this way, would NASA POWER be a good provider of temperature and humidity data to calculate THI considering Brazilian climatic conditions compared to INMET data?

Monteiro et al. (2018) compared meteorological data from 1997 to 2016 belonging to 203 INMET weather stations and the authors concluded that NASA POWER satisfactorily estimates daily temperature. Duarte and Sentelhas (2020) compared data from 10 INMET weather stations with data from NASA POWER collected between 1990 to 2013 and found correlations greater than 0.70 for minimum and maximum daily temperatures and average daily relative humidity. Similarly, Aguiar and Lobo (2020) evaluated 30 stations from 2004 to 2014 and reported correlations ranging from 0.21 to 0.99, and 0.50 to 0.96 for minimum and maximum daily temperatures, respectively, depending on the location. Therefore, the degree of agreement of data obtained via NASA POWER and INMET depends on where the data are collected.

In Canada, Rockett et al. (2023) demonstrated that the use of NASA POWER weather parameter estimates could replace weather station data in the calculation of THI. However, for Brazilian climatic conditions, such studies are still scarce. Therefore, we aimed to compare THI estimates obtained from INMET and NASA POWER meteorological information sources using linear regression and Pearson correlation.

Material and methods

Meteorological information from 2002 to 2021 (last 20 years) were gathered from 609 Brazilian INMET weather stations. Some filtering parameters was applied to guarantee data quality and were kept: i) weather stations with a minimum of five years of recorded data; ii) days with at least 19 daily hours recorded; iii) days with at least two measurements between hours 00:00–06:00, 06:00–12:00, 12:00–18:00, and 18:00–23:00 considering the Coordinated Universal Time (UTC); iv) minimum relative humidity levels of 12%; and v) data from automatic stations, as they provide hourly information. After the quality check, 489 weather stations with valid measurements remained for further analyses. The spatial distribution of the stations, classified according to the Köppen's climate classification map for Brazil (Alvares et al. 2013), is presented in Fig. 1.

THI was calculated using the following equation (NRC 1971):

$$THI = (1.8 \times T + 32) - [(0.55 - 0.0055 \times RH) \times (1.8 \times T - 26)],$$

where T is the air temperature in ºC, and RH is the relative humidity in %.

Hourly information on air temperature and relative humidity were selected from the INMET database considering the Coordinated Universal Time (UTC). Latitude and longitude data of the 489 weather stations (single point) were used to obtain the 2-m air temperature and 2-m relative humidity data in NASA POWER platform.

The hourly data from NASA POWER is provided in Local Solar Time format by default. Hence, the data in UTC format was obtained through the Application Programming Interface (https://power.larc.nasa.gov/docs/services/api/) using the following simple script in Python (Pandas interface):

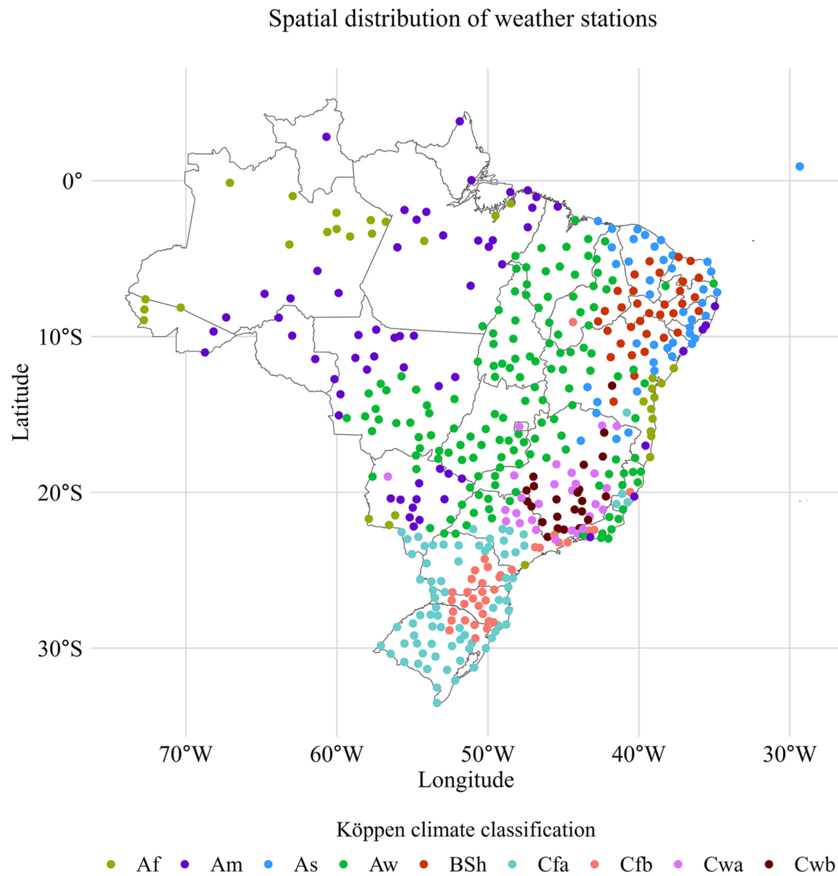
curl -X GET "https://power.larc.nasa.gov/api/temporal/hourly/point?parameters=T2M,RH2M&community=AG&longitude=AAA&latitude=BBB&start=YYYYMMDD&end=YYYYMMDD&format=ASCII&time-standard=UTC " -H "accept: application/json" > FILE_CITY_01.txt,

where **AAA** is the longitude and **BBB** is the latitude of the respective INMET weather station, in decimal format, with start date (**YYYYMMDD**) equal to 20,020,101 and end date equal to 20,211,231 (i.e. period from 01/01/2002 to 12/31/2021).

The variables evaluated were:

i) Hourly temperature (ºC, T_{HOURLY});
ii) Average daily temperature (ºC, $T_{AVERAGE}$);
iii) Maximum daily temperature (ºC, T_{MAX});
iv) Hourly relative humidity (%, RH_{HOURLY});
v) Average daily relative humidity (%, $RH_{AVERAGE}$);
vi) Minimum daily relative humidity (%, RH_{MIN});
vii) Hourly THI (THI_{HOURLY});
viii) Average THI ($THI_{AVERAGE}$), using the $T_{AVERAGE}$ and $RH_{AVERAGE}$; and
ix) Maximum THI (THI_{MAX}), using the T_{MAX} and RH_{MIN}.

Fig. 1 Spatial distribution of weather stations, separated according to the Köppen's climate classification map for Brazil (Alvares et al. 2013). Köppen's climate classification: Af = Tropical without dry season; Am = Tropical monsoon; As = Tropical with dry summer; Aw = Tropical with dry winter; BSh = Dry semi-arid low latitude and altitude; Cfa = Humid subtropical oceanic climate, without dry season and with hot summer; Cfb = Humid subtropical oceanic climate, without dry season and with temperate summer; Cwa = Humid subtropical with dry winter and hot summer; Cwb = Humid subtropical with dry winter and temperate summer



Descriptive statistics of the variables are reported in Supplementary Table 1. Although the variables obtained from INMET and NASA POWER displayed similar mean and standard deviation values, the amplitude of the INMET variables was slightly greater than that of the NASA POWER variables. That is, overall, the variables derived from INMET exhibited a lower minimum value and a higher maximum value.

The relationship between INMET and NASA POWER data was evaluated by Pearson's correlation coefficient (ρ), slope of linear regression (β), and regression evaluation metrics (mean absolute error, MAE; and adjusted coefficient of determination, R^2_{adj}). The β provided the pattern of the relationship between the variables, where lower MAE and higher R^2_{adj} indicate better adjustment. The ρ provided the degree of the relationship between the variables.

Three points of view were considered: the hourly THI (T_{HOURLY}, RH_{HOURLY}, and THI_{HOURLY}), the average THI of the day ($T_{AVERAGE}$, $RH_{AVERAGE}$, and $THI_{AVERAGE}$), and the maximum THI of the day (T_{MAX}, RH_{MIN}, and THI_{MAX}). For each THI calculation type (hourly, average daily and maximum daily), THI information was considered for the whole Brazil (THI general) and within regions according to the Köppen's climate classification map for Brazil (Alvares et al. 2013).

Results and discussion

The β and ρ parameters indicated a positive correlation between all INMET and NASA POWER variables. A better fit and higher correlation were verified when evaluated with the average daily values, i.e., $T_{AVERAGE}$, $RH_{AVERAGE}$, and $THI_{AVERAGE}$ (general), with higher ρ (0.92, 0.82, and 0.94, respectively), lower error, i.e., lower MAE (1.29, 6.61, and 1.60, respectively), and better regression fit, i.e., higher R^2_{adj} (0.85, 0.67, and 0.89, respectively) compared with the hourly and maximum daily THI parameters (Table 1). The hourly information (T_{HOURLY}, RH_{HOURLY}, and THI_{HOURLY} general) showed the lowest ρ (0.69, 0.56, and 0.79, respectively), highest MAE (3.46, 15.35, and 3.80, respectively) and lowest R^2_{adj} (0.49, 0.31, and 0.62, respectively) (Table 1).

Similar behavior was observed for THI analyzed according to Köppen's climate classification, i.e., the ρ were higher, regressions showed better fit and MAEs were lower for average daily THI, followed by maximum daily and hourly THI, respectively (Table 1). Within Köppen's climate classification, ρ coefficients among the hourly, average daily and maximum daily THI ranged from 0.63 (BSh) to 0.78 (Cfa); 0.86 (Cwb) to 0.96 (Cfa); and 0.69 (As) to 0.93 (Cfa), respectively (Table 1).

Table 1 Linear regression parameters, regression evaluation metrics and Pearson´s correlation coefficients comparing the weather parameters and temperature-humidity index (THI) values from the National Aeronautics and Space Administration Prediction of Worldwide Energy Resources (NASA POWER) with the corresponding values from the National Institute of Meteorology (INMET) weather stations, according to the THI calculation type (hourly, average daily or maximum daily)[a]

	Variable	β* ± SE	R^2_{adj}	MAE	ρ*
Hourly THI	Temperature (hourly)	0.67 ± 0.0001	0.49	3.46	0.69
	Humidity (hourly)	0.52 ± 0.0001	0.31	15.35	0.56
	THI general (whole Brazil)	0.77 ± 0.0001	0.62	3.80	0.79
	THI Köppen[b] Af	0.78 ± 0.0004	0.49	2.95	0.70
	THI Köppen Am	0.71 ± 0.0003	0.47	3.15	0.69
	THI Köppen As	0.59 ± 0.0003	0.41	3.23	0.64
	THI Köppen Aw	0.66 ± 0.0002	0.45	3.57	0.67
	THI Köppen BSh	0.53 ± 0.0004	0.40	3.33	0.63
	THI Köppen Cfa	0.72 ± 0.0002	0.61	4.60	0.78
	THI Köppen Cfb	0.72 ± 0.0003	0.55	4.99	0.74
	THI Köppen Cwa	0.64 ± 0.0004	0.42	4.31	0.65
	THI Köppen Cwb	0.63 ± 0.0005	0.42	4.48	0.65
Average daily THI	Temperature (daily average)	0.92 ± 0.0003	0.85	1.29	0.92
	Humidity (daily average)	0.76 ± 0.0004	0.67	6.61	0.82
	THI general (whole Brazil)	0.95 ± 0.0002	0.89	1.60	0.94
	THI Köppen Af	0.97 ± 0.0012	0.82	1.30	0.91
	THI Köppen Am	0.90 ± 0.0008	0.82	1.38	0.91
	THI Köppen As	0.82 ± 0.0014	0.65	1.61	0.80
	THI Köppen Aw	0.91 ± 0.0005	0.82	1.38	0.91
	THI Köppen BSh	0.91 ± 0.0012	0.82	0.92	0.90
	THI Köppen Cfa	0.90 ± 0.0005	0.91	1.68	0.96
	THI Köppen Cfb	0.89 ± 0.0013	0.76	2.76	0.87
	THI Köppen Cwa	0.87 ± 0.0014	0.76	1.84	0.87
	THI Köppen Cwb	0.92 ± 0.0017	0.73	2.37	0.86
Maximum daily THI	Temperature (daily maximum)	0.87 ± 0.0004	0.74	2.04	0.86
	Humidity (daily minimum)	0.75 ± 0.0004	0.61	9.09	0.78
	THI general (whole Brazil)	0.99 ± 0.0003	0.81	1.82	0.90
	THI Köppen Af	0.96 ± 0.0016	0.72	1.56	0.85
	THI Köppen Am	0.92 ± 0.0013	0.67	1.55	0.82
	THI Köppen As	0.82 ± 0.0020	0.48	1.85	0.69
	THI Köppen Aw	0.96 ± 0.0008	0.71	1.52	0.84
	THI Köppen BSh	0.88 ± 0.0018	0.63	1.56	0.79
	THI Köppen Cfa	0.93 ± 0.0006	0.86	1.88	0.93
	THI Köppen Cfb	0.92 ± 0.0016	0.67	3.10	0.82
	THI Köppen Cwa	0.90 ± 0.0018	0.69	1.79	0.83
	THI Köppen Cwb	0.93 ± 0.0022	0.62	2.77	0.79

[a]β = slope of the linear regression of weather parameters and THI values from NASA POWER on the corresponding INMET values; SE = standard error; R^2_{adj} = adjusted coefficient of determination; MAE = mean absolute error; ρ = Pearson's correlation coefficient

[b]Köppen's climate classification: Af = Tropical without dry season; Am = Tropical monsoon; As = Tropical with dry summer; Aw = Tropical with dry winter; BSh = Dry semi-arid low latitude and altitude; Cfa = Humid subtropical oceanic climate, without dry season with hot summer; Cfb = Humid subtropical oceanic climate, without dry season and with temperate summer; Cwa = Humid subtropical with dry winter and hot summer; Cwb = Humid subtropical with dry winter and temperate summer

* All β and ρ were significant (p-value < 0.0001)

Additionally, an hour-by-hour comparison was performed. In this instance, the variables were averaged based on UTC, incorporating data from all weather stations. This involved computing the mean hourly values of temperature, relative humidity, and temperature-humidity index considering all stations at each hour (mean of all 00:00 UTC, all 01:00 UTC, all 02:00 UTC, and so forth). This was conducted to verify if there exists a variation in the correlation between the different times of the day for the two information sources. In this case, correlations ranged from 0.73

to 0.89 for temperature values (Supplementary Table 2); 0.54 to 0.75 for relative humidity values (Supplementary Table 3); and 0.84 to 0.91 for temperature-humidity index values (Supplementary Table 4). There was no specific time of day found to have a higher correlation than others, nor was there a pattern of correlation based on the time of day.

Conclusions

NASA POWER satellite-based weather system was shown to be a suitable tool for obtaining the average and maximum THI values using information collected from Brazil, showing high correlations with THI estimates from INMET and good regression evaluation metrics. We recommend caution when using the NASA POWER data to calculate the hourly THI, since the correlation with INMET was slightly lower, although moderate to high (0.79).

Therefore, NASA POWER satellite-based weather system can assist studies that aim to analyze the impact of heat stress on livestock production in Brazil, providing additional data to complement the existing information available in the INMET database. It is particularly important for regions with low coverage by INMET.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00484-023-02493-5.

Funding This research received a financial support from "Conselho Nacional de Desenvolvimento Científico e Tecnológico" (CNPq, grant number 150156/2022–7) and EMBRAPA (SEG number 10.19.03.064.00.00).

Data availability The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests We certify that there is no conflict of interest with any financial organization regarding the material discussed in the manuscript. In addition, the authors have non-financial interests to disclose.

References

Aguiar JT, Lobo M (2020) Reliability and discrepancies of rainfall and temperatures from remote sensing and Brazilian ground weather stations. Remote Sens Appl Soc Environ 18:100301. https://doi.org/10.1016/j.rsase.2020.100301

Alvares CA, Stape JL, Sentelhas PC et al (2013) Köppen's climate classification map for Brazil. Meteorol Zeitschrift 22:711–728. https://doi.org/10.1127/0941-2948/2013/0507

Carrara ER, Petrini J, Salvian M et al (2021) Genetic parameters for milk yield and quality traits of Brazilian Holstein cows as a function of temperature and humidity index. J Anim Breed Genet 138:643–654. https://doi.org/10.1111/jbg.12636

Cordeiro ALL, Satrapa RA, Gregianini HAG et al (2020) Influence of temperature-humidity index on conception rate of Nelore embryos produced in vitro in northern Brazil. Trop Anim Health Prod 52:1527–1532. https://doi.org/10.1007/s11250-019-02141-4

Dauria BD, Sigdel A, Petrini J et al (2022) Genetic effects of heat stress on milk fatty acids in Brazilian Holstein cattle. J Dairy Sci 105:3296–3305. https://doi.org/10.3168/jds.2021-20914

Duarte YCN, Sentelhas PC (2020) NASA/POWER and DailyGridded weather datasets—how good they are for estimating maize yields in Brazil? Int J Biometeorol 64:319–329. https://doi.org/10.1007/s00484-019-01810-1

Ferraz JBS, de Felício PE (2010) Production systems - an example from Brazil. Meat Sci 84:238–243. https://doi.org/10.1016/j.meatsci.2009.06.006

INMET (2022) Management report INMET 2020–2022 (only in Portuguese). In: Natl. Inst. Meteorol. https://portal.inmet.gov.br/uploads/notastecnicas/Relatório-Gestão-Final_um.pdf. Accessed 16 Mar 2023

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge

Manica E, Coltri PP, Pacheco VM, Martello LS (2022) Changes in the pattern of heat waves and the impacts on Holstein cows in a subtropical region. Int J Biometeorol 66:2477–2488. https://doi.org/10.1007/s00484-022-02374-3

Monteiro LA, Sentelhas PC, Pedra GU (2018) Assessment of NASA/POWER satellite-based weather system for Brazilian conditions and its impact on sugarcane yield simulation. Int J Climatol 38:1571–1581. https://doi.org/10.1002/joc.5282

Negri R, dos Santos Daltro D, Cobuci JA (2021) Heat stress effects on somatic cell score of Holstein cattle in tropical environment. Livest Sci 247:104480. https://doi.org/10.1016/j.livsci.2021.104480

Nrc NRC (1971) A guide to environmental research on animals. National Academy of Science, Washington

Renaudeau D, Collin A, Yahav S et al (2012) Adaptation to hot climate and strategies to alleviate heat stress in livestock production. Animal 6:707–728. https://doi.org/10.1017/S1751731111002448

Rockett PL, Campos IL, Baes CF et al (2023) Phenotypic analysis of heat stress in Holsteins using test-day production records and NASA POWER meteorological data. J Dairy Sci 106:1142–1158. https://doi.org/10.3168/jds.2022-22370

Salvian M, Silveira RMF, Petrini J et al (2022) Heat stress on breeding value prediction for milk yield and composition of a Brazilian Holstein cattle population. Int J Biometeorol 67:347–354. https://doi.org/10.1007/s00484-022-02413-z

Santana ML, Bignardi AB, Pereira RJ et al (2016) Random regression models to account for the effect of genotype by environment interaction due to heat stress on the milk yield of Holstein cows under tropical conditions. J Appl Genet 57:119–127. https://doi.org/10.1007/s13353-015-0301-x

Santana ML, Pereira RJ, Bignardi AB et al (2020) Dual-purpose Guzerá cattle exhibit high dairy performance under heat stress. J Anim Breed Genet 137:486–494. https://doi.org/10.1111/jbg.12450

Stefani G, Santana Júnior ML, El Faro L, Tonhati H (2022) Genetics of tolerance to heat stress in milk yield of dairy buffaloes assessed by a reaction norm model. J Anim Breed Genet 139:215–230. https://doi.org/10.1111/jbg.12654

USDA (2023) USDA Agricultural Projections to 2032. In: Interag. Agric. Proj. Comm. https://www.ers.usda.gov/webdocs/outlooks/105853/oce-2023-01.pdf. Accessed 16 Mar 2023

West JW (2003) Effects of Heat-Stress on Production in Dairy Cattle. J Dairy Sci 86:2131–2144. https://doi.org/10.3168/jds.S0022-0302(03)73803-X