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RESEARCH ARTICLE

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Climate change impacts on heat stress in Brazil—Past, present, and future implications for occupational heat exposure

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Abstract

Climate change has caused an increased occurrence of heat waves. As a result of rising temperatures, implications for health and the environment have been more frequently reported. Outdoor labour activities deserve special attention, as is the case with agricultural and construction workers exposed to extreme weather conditions, including intense heat. This paper presents an overview of heat stress conditions in Brazil from 1961 to 2010. It also presents computer-simulated projections of heat stress conditions up to the late 21st century. The proposed climate analysis drew on historical weather data obtained from national weather stations and on reanalysis data, in addition to future projections with the ETA (*regarding the model's unique vertical coordinate*) regional forecast model. The projections took into consideration two Representative Concentration Pathways (RCP)—the 4.5 and 8.5 climate scenarios, namely, moderate and high emissions scenarios, respectively. Heat stress was inferred based on the wet-bulb globe temperature (*WBGT*) index. The results of this climate analysis show that Brazilian outdoor workers have been exposed to an increasing level of heat stress. These results suggest that future changes in the regional climate may increase the probability of heat stress situations in the next decades, with expectations of *WBGT* values greater than those observed in the baseline period (1961–1990). In terms of spatial distribution, the Brazilian western and northern regions experienced more critical heat stress conditions with higher *WBGT* values. As a response to the increased frequency trends of hot periods in tropical areas, urgent measures should be taken to review public policies in Brazil. Such policies should include actions towards better working conditions, technological development to improve outdoor labour activities, and employment legislation reviews to mitigate heat impacts on occupational health.

KEYWORDS

climate change, heat stress, occupational health, outdoor labour

1 | INTRODUCTION

Extreme climate events, such as heat waves, are significantly impacting many regions worldwide (Lewis and Karoly, 2013; Azhar *et al*., 2014; Bittner *et al*., 2014; Christidis *et al*., 2019). The impacts of heat waves on public health are associated with increasing morbidity or mortality rates (Jongsik and Kim, 2012; Lim *et al*., 2012; Hess *et al*., 2014; Laaidi *et al*., 2014; Tasian *et al*., 2014; Chien *et al*., 2016; Kim and Kim, 2017; Oray *et al*., 2018). Zhao *et al*. (2019) found that 6% of hospitalizations during the Brazilian hot season were associated with heat wave exposure. Particularly in Brazil, Ikefuti *et al*. (2018), Son *et al*. (2016) and Bell *et al*. (2008) reported a temperature impact on the mortality rate in the city of São Paulo. Similarly, Geirinhas *et al*. (2019) reported the same impacts in the city of Rio de Janeiro. Studies conducted in the state of São Paulo showed that heat exposure accounts for a substantial portion of deaths among sugarcane cutters (Bitencourt *et al*., 2012). Likewise, Roscani *et al*. (2017) found an elevated risk of heat stress in the state of São Paulo, responsible for a large part of the national sugarcane production. Heat stress is already a problem in many places around the world (Hyatt *et al*., 2010) and, according to a recent report by the International Labour Organization (ILO, 2019), the increasing climate change-related heat stress in outdoor work environments leads to prospects of negative occupational health impacts, loss of productivity, and millions of jobs lost worldwide.

Workers exposed to hot environments or those engaged in strenuous physical activities even at mild temperatures may be at risk for heat stress. When human physiological responses, responsible for heat exchange between the body and the environment, are no longer able to maintain body temperature below 38°C, the risk of heat-related illnesses increases. Regarding outdoor jobs, such as in agriculture and construction, heat stress is one of the main consequences of heat waves (Hyatt *et al*., 2010). Workers exposed to unfavourable thermal conditions for a sustained period of time, under heat stress, may face physiological strain, which can lead to general body weakness, altered psychosensory reactions, fluctuating risk perceptions, concentration lapses, accidents, and loss of productivity at work (Zander *et al*., 2015; Chang *et al*., 2017). Some authors (Garcia-Trabanino *et al*., 2015; Laws *et al*., 2015; Kiefer *et al*., 2016) reported chronic kidney disease in farmers associated with heat stress.

Since the last decades, several indices have been developed in order to predict the level of heat stress that workers might experience in hot environments. Yaglo and Minard (1957) proposed the wet-bulb globe temperature (WBGT) index with the aim of expressing environmental heat load as a combination of humidity, air movement, air temperature, and radiation effects. This is the most largely used index worldwide for occupational environment analysis and, in association with workload, it allows estimating occupational exposure limits to work in hot environments, considering the conditions under which thermal equilibrium can be maintained, that is, when no increases in core body temperature occurs. The *WBGT* is also suitable for evaluating possible needs for control measures to avoid excessive heat stress in the workplace. In Brazil, the use of *WBGT*, as recommended by the US National Institute for Occupational Safety and Health (NIOSH, 2020), is mandatory to monitor occupational exposure to heat, as established in annexes of the Brazilian Regulatory Standards NR 9 and NR 15. Such Regulatory Standards define the conditions under which preventive and corrective measures must be implemented, based on the Recommended Alert Limit and Recommended Exposure Limit defined by NIOSH, and provide guidance for managing work under heat stress (ME, 2019).

Therefore, it is necessary to implement adequate strategies and measures of risk management to mitigate heat-stress impacts on workers' health, even in the face of inherent uncertainties of climate projections. In order to be sustainable, organizations should improve their risk management processes in a structured way (Souza and Alves, 2018). The need to improve risk management is even more important for outdoor workers, who are affected by heat in an intensive manner (Lucas *et al*., 2014; Walther and Olonscheck, 2016; Krishnamurthy *et al*., 2017). Kiefer *et al*. (2016) pointed out that due to climate change, indoor or semi-indoor workers can likewise be affected by heat exposure and heat stress. Kikumoto *et al*. (2016) and Suzuki-Parker and Kusaka (2016), using future projections, showed that in Japan increased heat may impact the urban thermal environment with a significant reduction in safe labour hours. In studies conducted in China and Australia, Wang *et al*. (2019) and Chapman *et al*. (2019) pointed out that urbanization and climate change will pose serious health risks to people living in large cities due to extreme heat.

As Brazil has both tropical and subtropical climates, it is susceptible to atmospheric situations favourable to the occurrence of extreme heat (Cerne and Vera, 2011; Geirinhas *et al*., 2017; Feron *et al*., 2019). Over the past few years, extreme heat events have been reported by some authors in what concerns the increasing frequency and intensity of heat waves (Marengo and Camargo, 2008; Bitencourt *et al*., 2016; Ceccherini *et al*., 2016; Salviano *et al*., 2016; Geirinhas *et al*., 2017). Even during winter, the physical activity performance of healthy athletes adapted to heavy activities is impaired by heat. For instance, in the Soccer World Cup 2014 in Brazil, as observed by Nassis *et al.* (2015), the players' performance notably decreased in wintertime because of the days with high temperatures.

As a case in point, Bitencourt *et al.* (2019), based on *WBGT* values estimated from observed weather data, found how the risk of heat stress has evolved in the last decades. Through numerical simulations of *WBGT* values, Bitencourt *et al.* (2019) demonstrated the worst situation of heat stress during past heat wave events in Brazil's central-south region. Additionally, Oliveira *et al.* (2019) presented future projections of heat stress risks in the Brazilian semiarid region. According to a review by Nobre, Marengo and Soares, (2019) on future impacts of extreme warming on public health, Brazil will face aggravated heat stress conditions by the end of this century. These projections were estimated using the *WBGT* index, considering only the high emissions scenarios.

The present study evaluated past and current climate data and future projections related to heat stress, estimated by the *WBGT* index. Based on such past and future climate overview, the study discussed possible impacts on outdoor workers' health. Once such past and current heat stress situations are examined by comparison between observed, simulated and reanalysis data, the results obtained from future projections can be more accurately inferred.

2 | METHOD

2.1 | Observed data

The monthly mean air temperature (T), in °C, relative humidity (RH), in %, and wind velocity (V), in m·s^{-1}, were used for the *WBGT* estimation in the studied period from 1961 to 2010. These data were observed by the National Institute of Meteorology (INMET) network, which consists of 264 weather stations in Brazil—available at: www.inmet.gov.br/projetos/rede/pesquisa/. However, the number of observation points (N) depends on the year or decade to which the analysis refers. The study did not include years of which four or more months had any missing T, RH, or V values. For the decadal mean, the study also excluded the observational points whose annual data were missing five or more values.

2.2 | Reanalysis data

In order to fill the temporal and spatial missing data, *WBGT* decadal means for the historical period from 1961 to 2010 and the first decade of projections from 2008 to 2017 were also obtained from ERA reanalysis data. Specifically, the datasets used were ERA40 (Uppala *et al.*, 2005), prior to 1979, and ERA Interim (Berrisford *et al.*, 2009), posterior to 1979,—both available at www.ecmwf.int/en/forecasts/datasets/browse-reanalysis-datasets. The variables used were air and dewpoint temperatures, in °C, and wind velocity, in m·s^{-1}, at a $0.5 \times 0.5°$ horizontal resolution.

2.3 | Simulated data

The numerical simulation results were used for the historical (1961–2010) and future (2020–2099) climate projections. The simulations were performed using the ETA regional climate model, developed by the Center for Weather Forecasting and Climatic Studies (CPTEC) of the National Institute for Space Research (INPE), Brazil (Chou *et al.*, 2005). ETA refers to the Greek letter η, which is the symbol of the model's unique vertical coordinate (Mesinger, 1984). The results were obtained using the PROJETA Platform available at www.projeta.cptec.inpe.br. The simulations used a dynamical downscaling approach (Pesquero *et al.*, 2009; Chou *et al.*, 2014a; 2014b) at a 20-km horizontal resolution, nested with the HadGEM2-ES climate model from the Met Office Hadley Centre (MOHC). To run the analyses, the historical climate period in question corresponds to the reference period (Chou *et al.*, 2014a), and the future climate change projections up to 2099 considered two Representative Concentration Pathways (RCP): RCP 4.5 and RCP 8.5 (Moss *et al.*, 2010; Van Vuuren *et al.*, 2011a; 2011b). The RCP 4.5 scenario refers to moderate emissions while the RCP 8.5 scenario refers to high emissions. For the moderate RCP 4.5, radiative forcing increases almost linearly until about 2060 and then decreases until the end of the century. For the high RCP 8.5, there is a continuous increase in greenhouse gases up to 2099.

2.4 | *WBGT* estimation

For outdoor work environments with solar load, the *WBGT* index is given by Equation (1) (Yaglo and Minard, 1957).

$$WBGT = (0.7T_n) + (0.1T) + (0.2T_g), \tag{1}$$

where T, T_n, and T_g are, respectively, dry-bulb temperature, natural wet-bulb temperature, and globe temperature, all in °C.

Due to the fact that T_n and T_g are not routinely observed neither presented by numerical simulation

TABLE 1 Statistical values for T_n equation (Maia *et al.*, 2015)

	Coefficients	Standard error	*t* stat	*P*-value
Intercept	10.44966	1.34870	7.75	<.0001
V	−0.26523	0.08347	−3.18	.0019
Td	0.57175	0.04000	14.29	<.0001
T	0.19447	0.04139	4.70	<.0001
RH	−0.05134	0.01272	−4.04	<.0001

TABLE 2 Statistical values for T_g equation

	Coefficients	Standard error	*t* stat	*P*-value	Lower 95%	Upper 95%
T	1.374385	0.0378361	36.32472	$7.3887\ 10^{-65}$	1.29944	1.44933
UR	0.083627	0.0194963	4.28938	$3.7496\ 10^{-05}$	0.04501	0.12225
V	−1.021632	0.2367998	−4.31433	$3.4031\ 10^{-05}$	−1.49069	−0.552586

outputs, a number of researchers have calculated outdoor *WBGT* from standard weather data (e.g., Hunter and Minyard, 1999; Tonouchi *et al.*, 2006; Liljegren *et al.*, 2008; Gaspar and Quintela, 2009). Moreover, some of them (e.g., Hyatt *et al.*, 2010; Mohraz *et al.*, 2016; Lin *et al.*, 2017) have conducted trend analyses on *WBGT* using empirical methods, which, according to Bernard and Pourmoghani (1999), require less computation and are conceptually simpler.

In the present study, Equation (2) proposed by Maia *et al.* (2015) was used to estimate T_n.

$$T_n = 0.57175T_d + 0.19447T - 0.26523V - 0.05134RH + 10.44966 \tag{2}$$

where T_d is the dewpoint temperature, in °C, V is the wind velocity adjusted from 10 to 1.5 m, in m·s^{-1}, and RH is the relative humidity, in %.

Equation (2) was obtained through multiple linear regression and its details are shown in Maia *et al.* (2015), including information on how data were collected and the reliability and validity of this estimative model. Among the independent variables, T_d, which refers to the amount of water vapour in the air, presents the highest weight for obtaining T_n. On the other hand, RH, which strongly influences the formation of clouds, is the variable with the lowest weight in Equation (2). In summary, the model's linearity for T_n was verified through analysis of variance (ANOVA), which indicated that it is linear ($p < .0001$) and achieved a high correlation ($R^2 = 0.81$). The Student's *t* test indicated that all coefficients from the independent variables (RH, V, T, and T_d) were significant at a level up to 10% (Table 1).

Variables T, RH, V, and solar radiation are the four factors that influence outdoor *WBGT*; but solar radiation, which exerts an important role to T_g, is a difficult component to determine because of variable cloud cover (Hyatt *et al.*, 2010). Maia *et al.* (2015) determined T_g considering the thermal balance of the standard globe, for which they drew on solar radiation, among others observational data. In the present study, T_g is obtained through multiple linear regression given by Equation (3), which achieved skill scores similar to those obtained by Maia *et al.* (2015).

$$T_g = 1.374385T + 0.083627RH - 1.021632V \tag{3}$$

With the same 118-hr measuring period data series used by Maia *et al.* (2015), which were selected just for hot times ($T \geq 27°C$), the multiple linear regression for T_g (Equation (3)) was built here using Excel software. When testing variables T, RH, and V, the first result showed *P-value* for the intercept much higher than the significance level. For this reason, the regression model was reprocessed considering the intercept null. The model linearity was verified through analysis of variance (ANOVA), which indicated that Equation (3) is linear ($p < .0001$). The T_g model achieved a high correlation ($R^2 = 0.98$), and the Student's *t* test indicated that all coefficients from the independent variables (T, RH, and V) were significant at a level up to 10% (Table 2).

Based on Equations (2) and (3), the *WBGT* index can be obtained through Equation (1). In order to test the *WBGT* estimation skill used in this study, Equation (1) was applied for a dataset with a 165-hr measuring period, including values of T lower than 27°C.

Comparisons between estimated and observed *WBGT* achieved a high correlation ($R^2 = 0.78$), which means that

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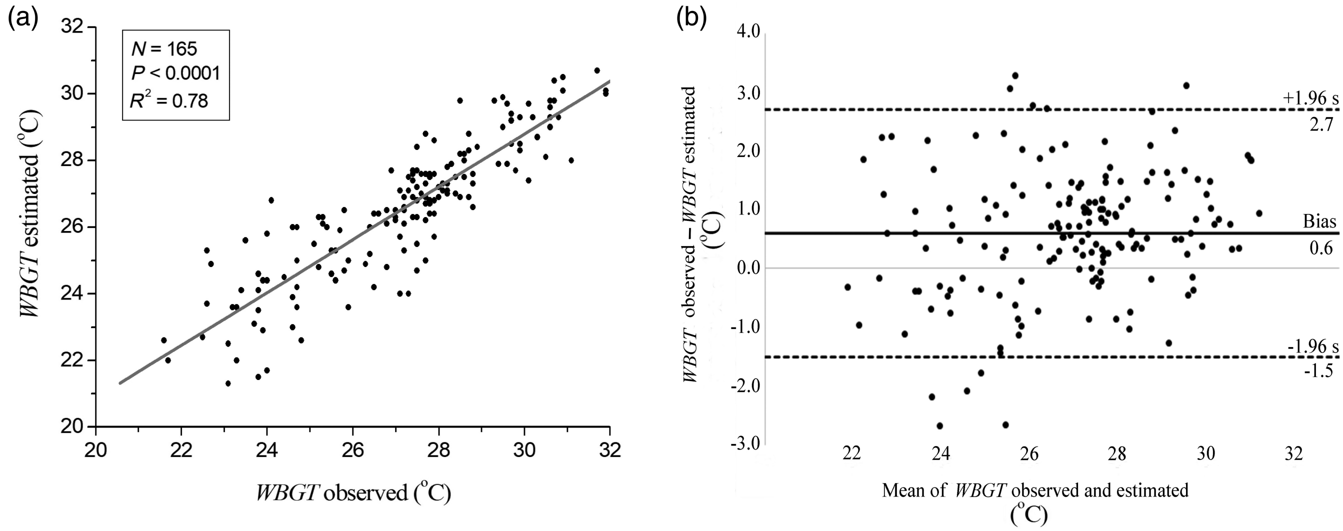

FIGURE 1 (a) Estimated *WBGT* compared with observed *WBGT* and (b) Bland and Altman plot, with representation of the limits of agreement (dotted line), from −1.96 s to +1.96 s, using a 165-hr data series. All data are in °C and *s* is the standard deviation

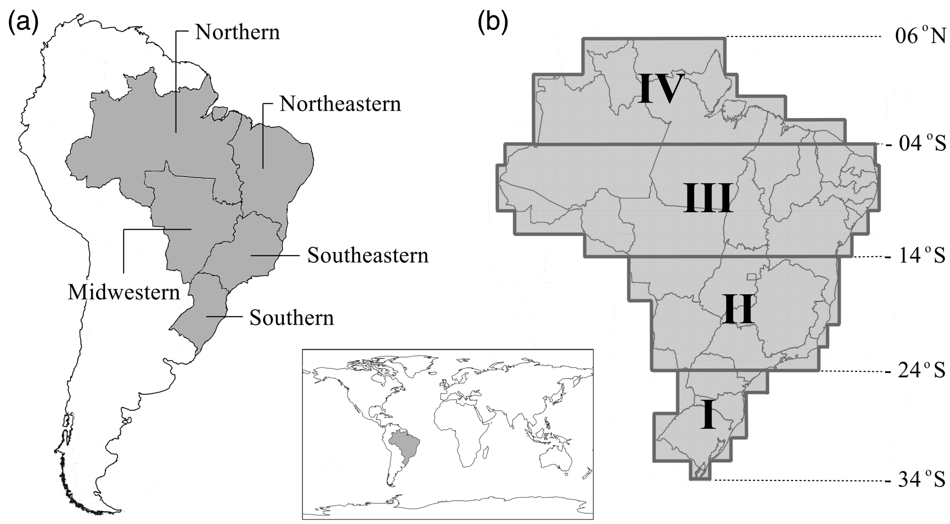

FIGURE 2 (a) South American and Brazilian domains (grey area) with regional boundaries: Southern (S), southeastern (SE), midwestern (MW), northeastern (NE) and northern (N). (b) Areas for the temporal trend analysis: I, from 34 to 24°S; II, From 24 to 14°S; III, From 14 to 4°S; IV, From 4°S to 6°N

78% of the variance of the data is explained by Equation (1) (Figure 1a). The Bland Altman analysis (Altman and Bland, 1983), in general, showed that the differences between estimated and observed *WBGT* are within the limits (±1.96 s), well balanced (above and below mean) for all *WBGT* values, and a little more concentrated close to the *WBGT* mean from 26 to 30°C (Figure 1b). Additionally, the bias value means that the *WBGT* index is, on average, underestimated at 0.6°C by Equation (1).

2.5 | Analysis

The spatial and temporal behaviour of *WBGT* was evaluated within the Brazilian territorial domain (Figure 2), considering quarterly, yearly and decadal periods. For the historical and future climate analyses of *WBGT*, the climatological mean ($\overline{WBGT}$) and anomalies ($WBGT'$) were calculated always considering (for anomalies) the climate period from 1961 to 1990, henceforth called $WBGT_{cli}$. For temporal trends, the Brazilian territorial domain was separated into four areas, as shown in Figure 2b, in order to specific, every 10° of latitude, the subtropical (areas I and II) and tropical (areas III and IV) regions. Using the ETA regional model, an additional analysis was carried out for the frequency of hot periods over the last decades and in the future. To that end, the daily data series were rebuilt, such that the *WBGT* of every single day was represented by a center moving average with a window of 15 days. Therefore, a day *d* is a representation of a 2-week period and was considered when $WBGT_d \geq WBGT_{d\text{-}cli} + s$, being $WBGT_{d\text{-}cli}$ the daily climate period built from 1961 to 1990, and s the standard deviation.

The *WBGT* values from observed and reanalysis data were used for the historical climate analysis (1961–2010), the skill scores of the regional model in the 1981–2000 period, and the first decade of climate projections (2008–2017) under considerations of RCPs 4.5 and 8.5. Skill scores were calculated by comparing $\overline{WBGT}$ files and by calculating the mean squared error (MSE) and percentage (%) of the observation points or gridded points (*N*) where the regional model correctly detected the $WBGT'$ signal. Comparisons between climate models and ERA reanalysis were performed by Kim *et al.* (2012). In the present study, the ERA gridded data were used to fill extensive areas of the Midwestern and Northern regions (Figure 2a) lacking observed data. In addition, the ERA gridded files tend to minimize local-scale effects, which does not often happen to the observational network, once the increased warming over the last decades in certain locations might have been caused by urbanization around the weather stations.

3 | RESULTS AND DISCUSSIONS

3.1 | Historical climate and simulation skill

Considering the area covered by the weather stations, it can be stated that heat stress conditions have intensified over the last few decades. It was observed that in tropical areas (Figure 3a), according to the global analysis by Lucas *et al.* (2014), there is a moderate risk to workers' health. Furthermore, heat intensification throughout Brazil has been recorded by other authors who also used observation data (e.g., Marengo and Camargo, 2008; Bitencourt *et al.*, 2016; Ceccherini *et al.*, 2016; Salviano *et al.*, 2016; Geirinhas *et al.*, 2017). In the Brazilian central-south (subtropical) region, $\overline{WBGT}$ is lower due to the incursion of cold air masses, which move behind cold fronts towards lower latitudes (Seluchi and Marengo, 2000). In the subtropical area, cold events are more frequent from June to August (austral winter), favouring the transport of cold and dry air from the south (Marengo *et al.*, 1997; Seluchi, 2009; Ricarte *et al.*, 2015).

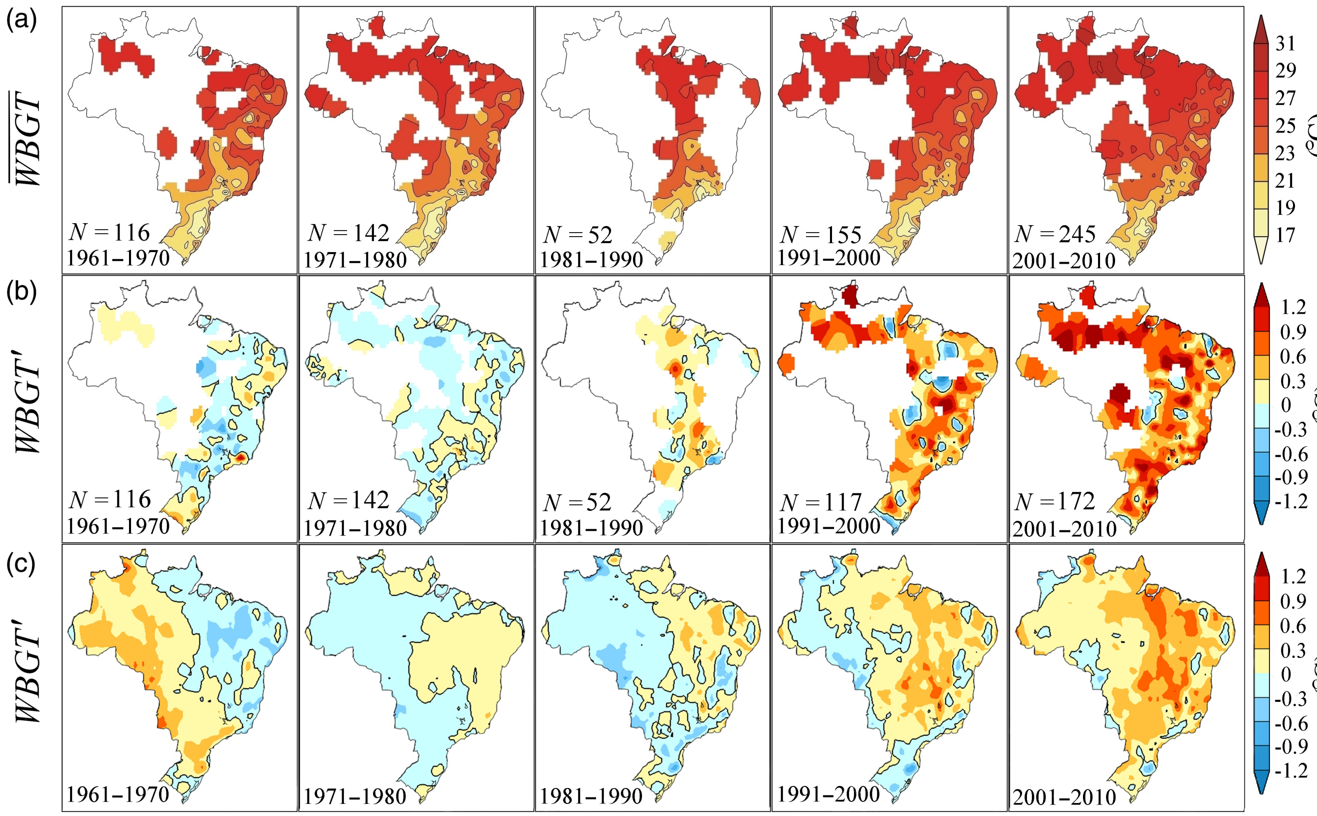

FIGURE 3 (a) Mean ($\overline{WBGT}$) and (b) anomalies ($WBGT'$) of the wet-bulb globe temperature index, in °C, by decade, from 1961 to 2010, based on observations of the National Institute of meteorology (INMET) network. The maps in row (c) are the same as those calculated for $WBGT'$ shown in row (b), but using ERA reanalysis. For rows (b) and (c), the climate period is from 1961 to 1990. The white areas in the maps in rows (a) and (b) represent areas lacking observed data: *N* is the number of observation points used in the analysis

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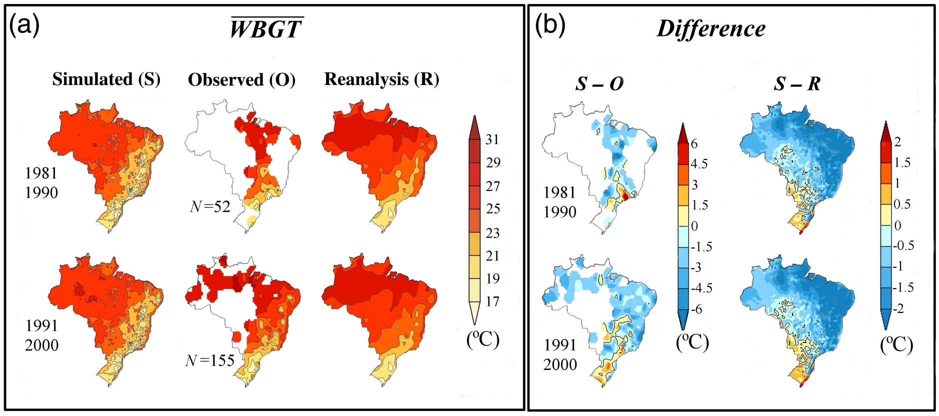

FIGURE 4 (a) Mean of the wet-bulb globe temperature index ($\overline{WBGT}$), in °C, for the 1981–1990 and 1991–2000 periods, from the ETA regional model simulated (S) data, INMET network observed (O) data (N is the number of observations), and ERA reanalysis (R) data. (b) Maps showing the difference between *Simulated* and *Observed* data and between *Simulated* and *Reanalysis* data. The white areas in the central maps in panel (a) and in the left maps in panel (b) represent areas lacking observed data

Although the Brazilian subtropical area has a winter season, with $\overline{WBGT} \leq 23°\text{C}$, high temperatures are normally recorded in spring (from September to November) and summer (from December to February). Moreover, in situations of extreme heat waves, there can be $WBGT > 30°\text{C}$ at hotter moments of the day (Bitencourt, 2019), which is a critical condition even for light workloads with metabolism near 200 W (FUNDACENTRO, 2017).

In 1960s and 1970s, $\overline{WBGT}$ was lower than the climatological mean from 1961 to 1990 on about half of the Brazilian area covered by weather stations (Figure 3b). However, as of the 1980s, most of the Brazilian territorial domains covered by weather stations presented $WBGT' > 0$, with a strong intensification of the anomalies as of 1990s. In the 2000s, both tropical and subtropical areas recorded $WBGT' \approx 1°\text{C}$ (Figure 3b), which is in line with the increased temperature trend found by Marengo and Camargo (2008) and Ceccherini *et al.* (2016), and with the increased heat stress risk found by Bitencourt *et al.* (2019). With an increased $WBGT'$ with a spatially homogeneous behaviour over the decades, the ERA reanalysis data confirmed heat stress conditions intensified in the areas covered by weather stations (Figure 3c). For the areas without weather stations, the ERA reanalysis revealed $WBGT' > 0$ in the 1960s and $WBGT' < 0$ in the 1970s and 1980s. However, from the 1990s, $\overline{WBGT}$ became gradually higher than that for the 1961–1990 climate period, with $WBGT' > 0$ in almost all the Brazilian domain in the 2000s (Figure 3c).

The comparison between the results of the ETA regional model and the observed/reanalysed data for the 1980s and 1990s showed low discrepancy, as evinced by qualitative analysis of $\overline{WBGT}$ for simulated (S), observed (O), and reanalysed (R) data (Figure 4a) and by the difference between such maps (Figure 4b). The spatial evaluation of the differences, calculated only for the observation points with sufficient data, showed simulation results underestimated in tropical areas and overestimated in subtropical areas, with differences of about 1.5°C (S–O, in Figure 4b). The comparison between the ETA simulation and the ERA reanalysis confirmed this result, but with lower difference values (S–R, in Figure 4b). After analysing the entire Brazilian domain through the difference evidenced in S–R, as shown in Figure 4b, it was noted that for the 1980s and 1990s the simulation results were overestimated in almost all subtropical areas and underestimated in almost all tropical areas, in up to 2°C. In other words, precisely in the areas where $\overline{WBGT}$ is higher, the simulation yielded values lower than those observed or reanalysed.

The skill scores calculated for areas I–IV (as shown in Figure 2b) and for the entire period of the historical climate analysis showed that the ETA regional model simulated correctly the $WBGT'$ signal in more than 60% of the observation points for almost all cases analysed (Table 3). In the analysis of observed data, the means percentages of locations with anomalies signals correctly simulated for the entire period of the historical climate analysis (1961–2010) were 79, 67.8, 72, and 78.8% in areas I–IV, respectively. Using the gridded ERA reanalysis, the means percentages in areas I–IV were, respectively, 46.4, 52.6, 50, and 57.2%. On the other hand, the maximum MSE was from 0.2 to 0.3°C: The MSE means for the 1961–2010 period in areas I–IV were, respectively, 0.09241, 0.07263, 0.09327, and 0.10834°C when compared with observed data, and 0.16110, 0.15989, 0.16043, and 0.18357°C when compared with reanalysis data (Table 3).

TABLE 3 Parameters (*par*) for quantitative evaluation of the ETA regional model skill, in terms of *WBGT′*, upon comparison of the ETA simulation with observed data (upper table) and with reanalysis data (lower table)

Area	par	1961–1970	1971–1980	1981–1990	1991–2000	2001–2010
Observed data						
I	*N*	25	26	6	22	30
	n (%)	64	73	83	82	93
	MSE (°C)	0.21107	0.09728	0.03398	0.04544	0.07429
II	*N*	43	57	25	68	91
	n (%)	79	88	68	81	23
	MSE (°C)	0.18342	0.06627	0.07909	0.08794	0.11153
III	*N*	40	37	13	43	92
	n (%)	68	97	46	58	91
	MSE (°C)	0.13621	0.09265	0.08098	0.07133	0.08517
IV	*N*	8	22	8	22	32
	n (%)	88	95	88	64	59
	MSE (°C)	0.06715	0.18599	0.05730	0.09860	0.13268
Gridded ERA reanalysis						
I	*N*	321				
	n (%)	41	26	49	32	84
	MSE (°C)	0.15037	0.03826	0.06084	0.26920	0.28684
II	*N*	823				
	n (%)	32	31	37	76	87
	MSE (°C)	0.16899	0.17224	0.11729	0.13319	0.20775
III	*N*	1,545				
	n (%)	45	13	39	63	90
	MSE (°C)	0.14520	0.10625	0.14619	0.15015	0.25434
IV	*N*	889				
	n (%)	41	48	42	73	82
	MSE (°C)	0.10096	0.23776	0.17988	0.12180	0.27759

Note: N, Number of observation points or grid points of ERA reanalysis; *n*, Percentage (%) of *N* for which the ETA model detected correctly the *WBGT′* signal; MSE, Mean squared error (mean among *N*, for each area and each decade). The boundaries of areas I–IV are presented in Figure 2.

3.2 | First years of the projection

The $W\bar{B}GT$ projections for the 2008–2017 period underestimated the *WBGT* in most part of the tropical area and in a smaller part of the subtropical area, according to the differences displayed in Figure 5a. Based on the quantitative analysis, for the first decade of projections, there is a similarity between the projections of scenarios RCP 4.5 and 8.5 (Figure 5b). The comparison of these two projections with the observed and reanalysed *WBGT′* showed that both scenarios presented ~94% of the observation points and ~91% of the reanalysed grid points with *WBGT′* signals correctly provided (Figure 5b). The MSE for the 2008–2017 period was slightly higher in comparison with that of the decades tested for the 1961–2010 period. Figure 5b indicated that, visually, there is a difference between RCP 4.5 and 8.5 projections, mainly where there is no availability of weather stations. This result explains why there is a similarity between the MSE values for the observed map and a difference of ~0.4°C for ERA reanalysis map. Therefore, these results point out that the model underestimated the heat stress conditions, mainly at lower latitudes (tropical). In other words, if the current trend standard was kept for the following decades, the future projection (2020–2099) would also underestimate warming.

In fact, in general, all the Coupled Model Intercomparison Project (CMIP5) multi-model ensemble agrees that temperatures are projected to substantially increase (above 1°C) in South America. On the other

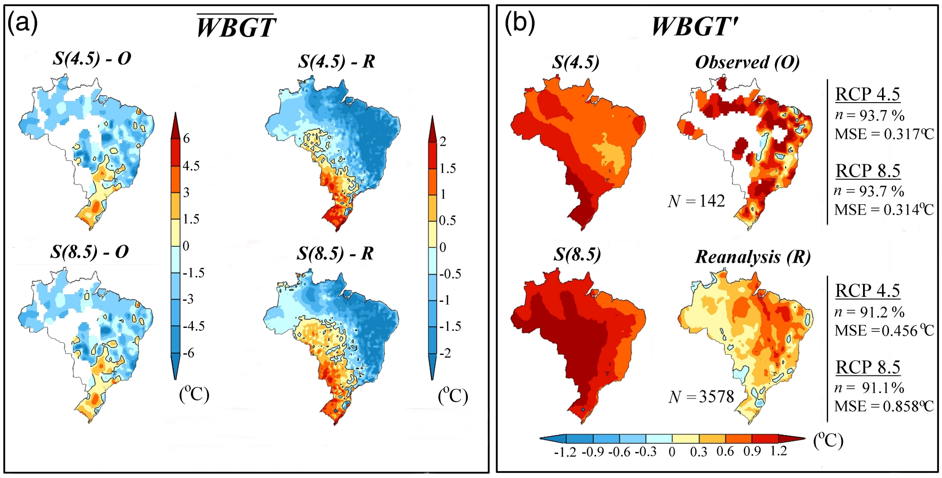

FIGURE 5 ETA regional model skill score for the first decade (2008–2017) of projections performed by a quali-quantitative comparison between simulated and observed data and between simulated and reanalysed data of (a) $\overline{WBGT}$ and (b) $WBGT'$, in °C. *S(4.5)* and *S(8.5)* are, respectively, the projections under consideration of scenarios RCP 4.5 and 8.5. In panel (a), *S–O* and *S–R* represent, respectively, the difference between *Simulated* and *Observed* data and *Simulated* and *Reanalysed* data. In panel (b), *n* is the percentage (%) of observation points or grid points (*N*) for which the model correctly simulated the $WBGT'$ signal, and MSE is the mean squared error (°C). The white areas in some of the maps represent the areas lacking observed data

hand, uncertainties are inherent in any climate projections, and these are derived from several sources. In the literature, there are several proposed methods for combining projections from ensembles of climate models and estimating an uncertainty range, but none of them have been shown to be the most suitable or reliable, what becomes this subject far from being trivial (Knutti *et al.*, 2010). Evidently, the methodology used here has limitations, as well as the fact of using one Regional Climate Model (RCM). However, the regional simulation uncertainties over South America are still present in many RCMs, as shown by Ambrizzi *et al.* (2019). Also, a historical list of RCM simulations, including the model used here, over South America shows improvement in regions where the mesoscale forcing modulates the regional climate, so the RCM used in the present study would not compromise the obtained results.

3.3 | Future projections

The future projections performed show a gradual increase of $\overline{WBGT}$ from 2020 to 2099. Even considering moderate emissions scenarios (RCP 4.5), the trends show enlargement of the area with $\overline{WBGT} > 27°C$ up to the end of the century: as of the 2070s, areas with $\overline{WBGT} > 29°C$ emerge in the Northern region (Figure 6). *WBGT* from 27 to 29°C would affect actives with metabolism (workload) near 380 and 250 W, respectively. Heat stress conditions will be even more critical if the global behaviour of greenhouse gases emissions follows the high emissions scenario (RCP 8.5). In this case, the projections indicate huge areas of the Brazilian domain with $\overline{WBGT} > 27°C$ by 2050, $\overline{WBGT} > 29°C$ from 2050 to 2080, and $\overline{WBGT} > 31°C$ as of 2080. In the Northern and Midwestern regions, also in part of the subtropical area (i.e., part of areas II–IV), *WBGT* tends to be more critical. The $WBGT'$ maps with RCP 8.5 show this result clearly: spatial cover of $WBGT' > 3°C$ expanding over the country west as of 2050, $WBGT' > 4°C$ by the 2070s, and $WBGT' > 5°C$ in huge areas as of 2080 (Figure 6). The results found here corroborate the findings made by Dong *et al.* (2015) who, using a high emissions scenario, found medium and high heat risks from 2030 to 2050, and high and very high heat risks from 2080 to 2100. For many regions worldwide, other authors have established a relationship between future heat stress increases and loss of productivity at work (e.g., Dunne *et al.*, 2013; Kjellstrom *et al.*, 2013; Zander *et al.*, 2015; Lee *et al.*, 2018).

Another fact that stood out in the projections for the following decades is the expansion of high *WBGT* areas where such an aspect had not been previously recorded. This indicates that some areas of Brazil, where currently there are no critical heat conditions (i.e., with low values of *WBGT*), will become more susceptible to heat stress. In other words, the western area of Brazil, mainly in the Midwestern region, will remain the hottest area. In that region, 12.4% of workers work in the rural area, according to the latest agricultural report of 2017 (IBGE, 2019). In comparison with the other Brazilian

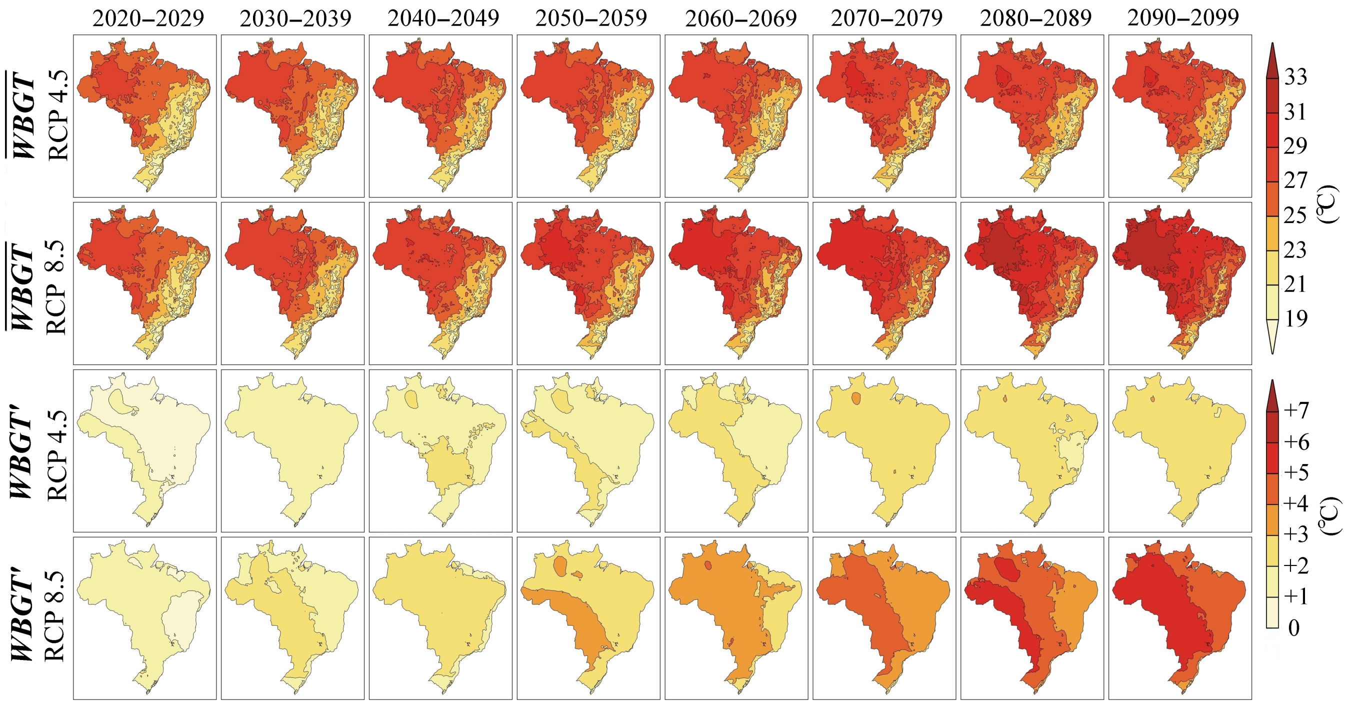

FIGURE 6 Projection for the mean ($W\bar{B}GT$) and anomalies ($WBGT'$) of the wet-bulb globe temperature under consideration of the RCP 4.5 and 8.5 scenarios, as indicated on the left. The values (scales on the right) represent each decade (at the top), from 2020 to 2099

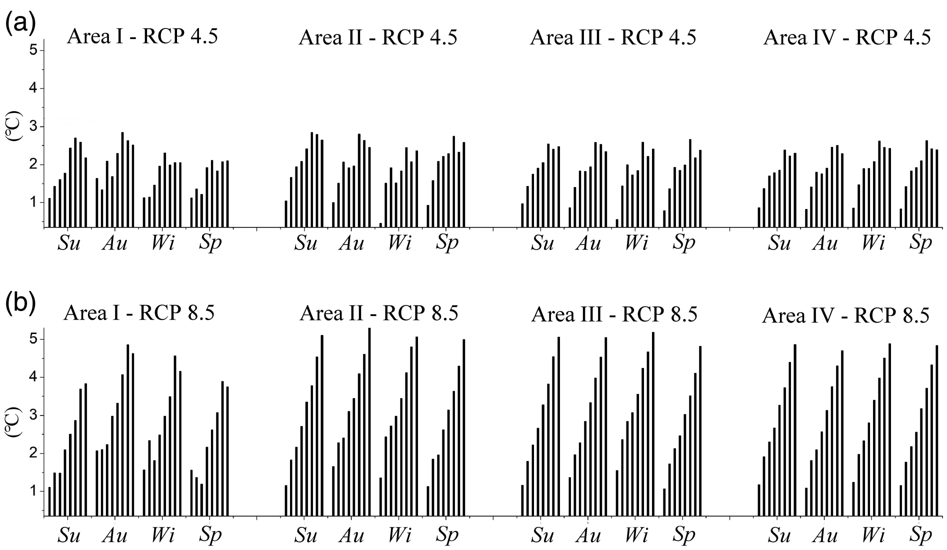

FIGURE 7 Quarterly projections of *WBGT* anomalies ($WBGT'$), in °C, based on scenarios RCP (a) 4.5 and (b) 8.5. Quarters are indicated in the horizontal axis: *Su*, Summer (DJF); *Au*, Autumn (MAM); *Wi*, Winter (JJA); *Sp*, Spring (SON). For each quarter, the bars from left to right show $WBGT'$ for 2020–2029, 2030–2039,…, and 2090–2099. Areas I–IV (according to Figure 2b) are marked at the top of the graph. $WBGT'$ is calculated based on the climate period (1961–1990) $[WBGT' = W\bar{B}GT - W\bar{B}GT_{cli}]$

regions, the Midwestern one leads in terms of agricultural production and, therefore, this region has a considerable labour contingent in outdoor work environments.

The seasonal evaluation evinced that all areas under consideration presented $WBGT' > 0$ in all seasons and all climate scenarios (Figure 7). In addition, $WBGT'$ gradually increased from 2020 to 2099 in almost all of the projected situations. Only at the end of the century (for RCP 4.5), a subtle decrease in the trend of $WBGT'$ (even always with $WBGT' \approx 2°C$) can be seen in summer and autumn in areas I and II (Figure 7a). This result is probably due to the radiative forcing, which, in the RCP 4.5 scenario, does not increase linearly until the end of the century. Considering the RCP 8.5 scenario, some variability of $WBGT'$ appeared in area I (subtropical) over the 2020–2099 period, but always with $W\bar{B}GT$ above the climatological mean in all seasons. For the same scenario (RCP 8.5), the other areas (II–IV) in all four seasons

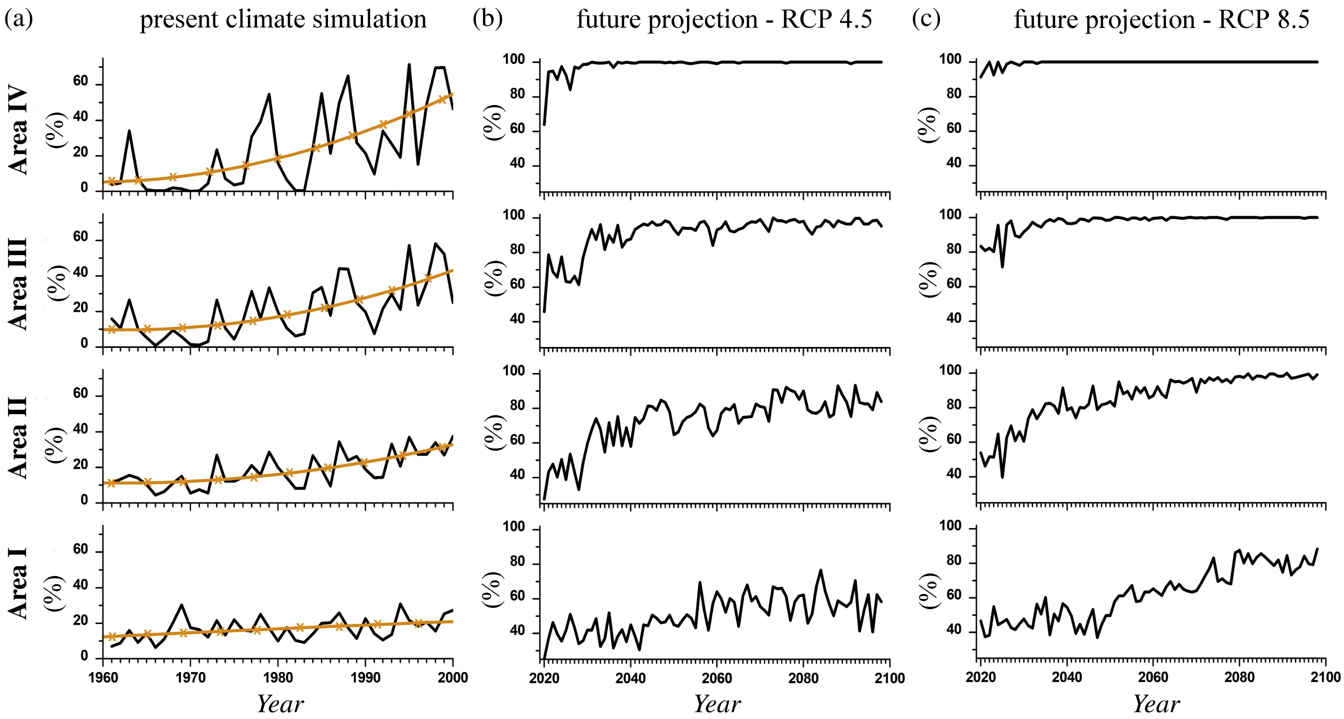

FIGURE 8 Annual frequency of 2-week hot periods (black line, in %) ($WBGT_d \geq WBGT_{d\text{-}cli}$ + s, where $WBGT_d$ is the moving average of day *d* centred on a 15-day window, $WBGT_{d\text{-}cli}$ is the climatology of these 15 days, built from the 1961 to 1990 period, and s is the standard deviation around climatology). The frequencies of hot periods are presented for (a) historical climate simulations and for future projections, considering scenarios (b) RCP 4.5 and (c) RCP 8.5. Areas I–IV (as displayed in Figure 2b) are indicated on the left of the graphs. The dashed line, for the historical climate, represents a polynomial regression of frequency

showed $WBGT'$ increasing linearly from ~1.27 (in the 2020s) to ~4.97°C (in the 2090s) (Figure 7b). Therefore, in areas I and II, under the action of cold air masses from June to August (Marengo *et al*., 1997; Seluchi, 2009; Ricarte *et al*., 2015), the winters from 2020 until 2099 will be gradually less severe (milder). On the other hand, in the same areas I and II, with occurrence of heat waves (Bitencourt *et al*., 2016), spring and summer will present more and more critical heat stress conditions until the end of the century.

3.4 | Two-week hot periods frequency (1961–2000 and 2020–2099)

Brazil has 91 million workers, of whom about 15 million work in the agricultural sector and almost 7 million in the construction sector. Therefore, considering just these two sectors with outdoor activities, Brazil has a contingent of more than 20 million workers directly exposed to natural environmental conditions. Areas I and II, which cover Southern and Southeastern regions and a huge part of the Midwestern region, with about 6.7 million labour contingents linked to agriculture, have shown an increase in the annual frequency of hot periods over the historical climate period (1961–2000). In area I, the increase in frequency was more subtle; however, it changed from ~11.6% in 1961 to ~21.6% in 2000 (Figure 8a). In area II, the increase in the number of hot periods yearly was more pronounced, mainly as of the 1990s: the frequency changed from ~11.6% in 1961 to 37.5% in 2000. In areas III and IV, which cover part of the Midwestern region and most part of the Northern and Northeastern regions, with near 8.5 million of agricultural workers, an increase in frequency of hot periods was recorded, mainly as of the 1980s. In area III, the frequency changed from 10.3 to 50.3%, from 1961 to 2000. In area IV, this percentage increased from 5.2 to 64.5% over the historical climate period (1961–2000) (Figure 8a). The results for frequency of hot periods within the historical climate period are consistent with previous studies reporting warming in the past decades in Brazil (Marengo and Camargo, 2008; Bitencourt *et al*., 2016; Ceccherini *et al*., 2016; Salviano *et al*., 2016; Geirinhas *et al*., 2017). This has currently led to considerably difficult situations for outdoor workers, as recently reported by Bitencourt *et al*. (2019) in a study addressing areas I and II.

In the future projection period (2020–2099), the annual frequency of hot periods increases in all areas, for both climate scenarios. In area I, such an increase in frequency is approximately below 60% in the 2060s, slightly rising until the end of the century for the moderate emissions scenario (RCP 4.5); while for the high emissions scenario (RCP 8.5), frequency becomes more critical, reaching ∼80% in 2099 (Figure 8c). In area II, in both climate scenarios, frequency remains below 60% only in the 2030s. After that, the number of hot periods increases gradually, reaching ∼80% (moderate emissions scenario) or 100% (high emissions scenario) by the end of the century (Figure 8b,c). In areas III and IV, which cover the tropical regions of Brazil, for both climate scenarios the projections indicate environmental conditions unfavourable for outdoor work almost all year round (taking as reference the 1961–1990 period). For nearly the entire 2020–2099 period in area III, the trend is from 80 to 100% yearly with the occurrence of hot periods, considering the moderate emissions scenario (RCP 4.5) (Figure 8b). In the same area III, and considering the high emissions scenario (RCP 8.5), the trend is for hot periods almost all year round, as of the 2030s. Regarding area IV, considering both scenarios (moderate and high emissions), the frequency of hot periods will be close to 100% nearly the entire 2020–2099 period.

The hot-period frequency evaluation was performed taking as a reference the climate period from 1961 to 1990. In the three decades of this evaluated period, the processes indicated that outdoor work activities back then were different from the current scenario and, very likely, will be even more different in the future. Therefore, it is expected that at least part of the future worsening of heat stress conditions will be compensated by improvements in work conditions and by access to new technologies and workplace heat management. There are many ways to manage occupational heat stress, including developing regional thresholds and operationalization of night work for workplace heat management, optimizing work patterns to minimize heat stress, encouragement of self-pacing and reductions in heat exposure, improved access to hydration, acclimatization and fitness programs, and reorientation of attitudes towards working in the heat among both employees and employers. It may be advantageous for employers to implement strategies that help employees manage heat impacts away from work, but there is far less research in this area (Zander *et al.*, 2015). Another issue for employers and the general economy is regarding productivity at work, which can be decreased because of extreme heat (Zander *et al.*, 2015; Krishnamurthy *et al.*, 2017; Lee *et al.*, 2018; ILO, 2019). On the other hand, this lost productivity in the workplace can be minimized with the adoption of managing occupational heat stress. However, evidently, any new technology or/and workplace heat management practice to minimize the heat impact on outdoor workers needs to be included in public policies and to be effectively accessible for workers.

4 | CONCLUSIONS

The proposed analysis comprising the 1961–2010 period allows concluding that, based on *WBGT* heat stress, outdoor workers in Brazil have been exposed to extreme heat conditions, mainly since the 1990s. Additionally, the projections based on scenarios RCP 4.5 and 8.5 predict even more critical heat stress conditions for the next decades, with increasing *WBGT*. Particularly for the end of the 21st century, the results point to *WBGT* far above the climatological mean values registered between 1961 and 1990. For instance, the anomalies projected range from 1 to 4°C for the moderate emissions scenarios, and from 3 to 7°C for the high emissions scenarios. Under such conditions, the impact on the outdoor workers' health may be strong, even if they perform light workloads.

Regarding spatial distribution, the present analysis shows that the most critical area subject to heat stress is the western part of Brazil, mainly within the Midwestern region. Particularly, it is in the Midwestern region that most workers perform outdoor activities under a heavy workload. It was observed that the frequency of 2-week hot periods per year with high *WBGT* increased considerably in the historical climate period, indicating that extreme occupational heat exposure in outdoor work environments is already a reality in Brazil. Besides, the study projected an increased occurrence of high *WBGT* for the next decades. Considering that high *WBGT* conditions are supposed to be more frequent in the near future, serious prejudicial impacts, such as body weakness, altered psychosensory reactions, fluctuating risk perceptions, concentration lapses, accidents, loss of productivity, and even chronic kidney disease, are expected to affect outdoor workers every year.

Some limitations regarding the results of this study and the need for further investigation on the relevant topic should be highlighted. Although the results are centred on spatial distribution and temporal trends of occupational heat exposure, the application of the formula, based on hourly-resolution data, may present some limitations for daily average data. In addition to limitations addressed to the estimation method, the daily average *WBGT* results were not able to detail the behaviour of occupational heat exposure in an entire work shift, which in Brazil can be extremely critical in heat wave situations, as pointed out by Bitencourt *et al.* (2019). Another limitation is related to the results of the climate projections. Although previous results suggest, with confidence, that models reproduce many features of present-day climate and climate variability on a wide range of time scales, several studies have shown that "model errors" remain (IPCC, 2013). As this study provides an overview of how heat stress in Brazil will respond to climate change and provides policy-relevant climate information, although there is a number of issues that illustrate the need of future work to address them. The need of future works includes the application of a multi-model ensemble to quantify uncertainty in present-day and future climate projections (Collins *et al.*, 2011), as well as impacts of internal variability (Hawkins and Sutton, 2009) and ocean–atmosphere feedback (Cai *et al.*, 2020), which could lead to a better representation of regional-scale processes.

The conditions of extreme heat exposure in outdoor work environments are expected to cause, among other things, increased vulnerability to heat-related diseases among outdoor workers. Despite positive changes in working conditions that should take place in decades to come, some labour sectors such as the agricultural and construction ones will still require from workers a heavy workload. Therefore, this scenario of worsening, as per *WBGT* trends, calls for an urgent review of public policies and regulations. Such new public policies and regulations should provide for technological development towards safer working conditions. Regarding technological development, it is vital that improvement be made in terms of individual and collective procedures, such as rest-pause areas and appropriate clothing for extreme heat. Furthermore, it is also recommended that risk communication tools be developed, as well as studies evaluating the heat control measures currently adopted. Finally, regulations should focus on standards aimed at preventive and corrective actions for extreme heat measures to minimize possible negative impacts on occupational health.

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