Impacts of heat stress conditions on mortality from respiratory and cardiovascular diseases in Brazil

Impactos das condições de estresse térmico na mortalidade por doenças respiratórias e cardiovasculares no Brasil

Beatriz Fátima Alves de Oliveira[a]

Ludmilla da Silva Viana Jacobson[b]

Letícia Palazzi Perez[c]

Ismael Henrique Silveira[d]

Washington Leite Junger[e]

Sandra de Souza Hacon[f]

[a] *Doctor in Sciences by the Sério Arouca National Public Health School (ENSP/FIOCRUZ), Oswaldo Cruz Foundation Regional Office in the state of Piauí, Teresina, PI, Brazil*
E-mail: beatrizenf@gmail.com

[b] *Doctor in Collective Health by the Social Medicine Institute, (IMS/UERJ), Universidade Federal Fluminense (UFF), Niterói, RJ, Brazil*
E-mail: ludmillaviana@yahoo.com.br

[c] *Doctor in Physical Geography, Federal University of Paraíba (UFPB), João Pessoa, PB, Brazil*
E-mail: leticia.palazzi@gmail.com

[d] *Doutor in Collective Health by the Social Medicine Institute, (IMS/UER), Federal University of Bahia (UFBA), Salvador, BA, Brazil*
E-mail: ismaelhsilveira@gmail.com

[e] *Doctor in Collective Health by the Social Medicine Institute, (IMS/UER), State University of Rio de Janeiro (UERJ), Rio de Janeiro, RJ, Brazil*
E-mail: wjunger@ims.uerj.com

[f] *Doctor in Biosciences by the Federal Fluminense University (UFF), National School on Public Health (ENSP/FIOCRUZ), Rio de Janeiro, RJ, Brazil*
E-mail: shacon@ensp.fiocruz.br

doi:10.18472/SustDeb.v11n3.2020.33970

Received: 08/09/2020
Accepted: 27/10/2020

ARTICLE – DOSSIER

Data and results presented in this article were developed under the project of the "Fourth National Communication and Biennial Update Reports of Brazil to the Climate Convention", coordinated by the Ministry of Science, Technology and Innovations, with the support of the United Nations Development Programme and resources of the Global Environment Facility, to which we offer our thanks.

ABSTRACT
This study assesses the risk of exposure to heat stress conditions and their potential impact on mortality from cardiovascular and respiratory diseases in Brazilian capital cities for warming levels of 1.5 °C, 2.0 °C and 4.0 °C in the RCP8.5 scenario. The risk of exposure and the impact of heat stress conditions on mortality were measured by the Wet Bulb Globe Temperature (WBGT) index. The impact on health was estimated by applying exposure-response curves between WBGT and health outcomes in the projections. The potential impact on mortality was measured by attributable fraction of mortality due to heat stress. The results showed an increase in heat stress conditions for Brazil, especially in the Northern and Center-Western regions. The estimated curves showed an association between the WBGT and mortality by cardiovascular and respiratory diseases in Brazil, with an upward impact trend, according to the levels of warming and heterogeneous results among the capitals.

Keywords: Climate Change. Heat Stress. Wet Bulb Globe Temperature (WBGT). Cardiovascular Diseases. Respiratory Diseases.

RESUMO
O presente estudo avaliou o risco da exposição às condições de estresse térmico e seu potencial impacto na mortalidade por doenças cardiovascular e respiratória nas capitais brasileiras, de acordo com os níveis de aquecimento 1.5°C, 2.0°C e 4.0°C, no cenário RCP 8.5. O risco da exposição e o impacto das condições de estresse térmico sobre a mortalidade foram avaliados por meio do indicador Wet Bulb Globe Temperature (WBGT). Para o impacto na saúde, estimaram-se as curvas exposição-resposta entre WBGT e os desfechos em saúde e, em seguida, essa curva foi aplicada nas projeções para quantificar a fração atribuível da mortalidade devido ao estresse térmico. Os resultados mostraram um aumento das condições de estresse térmico para o Brasil, sobretudo nas regiões Norte e Centro-Oeste. As curvas estimadas mostraram associação entre WBGT e mortalidade por doenças cardiovasculares e respiratórias, com tendência de aumento dos impactos conforme os níveis de aquecimento e resultados heterogêneos entre as capitais.

Palavras-chave: Mudanças Climáticas. Estresse Térmico. Wet-Bulb Globe Temperature (WBGT). Doenças Cardiovasculares. Doenças Respiratórias.

1 INTRODUCTION

Climate change is among the current major environmental problems and among the ten worst threats for global health listed by the World Health Organization in 2019 (WHO, 2019). Implications on health will become ever more urgent as climate change affects the quantity and quality of water and food, air pollution increases, vector distribution and dynamics change, and extreme events intensify (IPCC, 2014). It is estimated that between 2030 and 2050, climate change might cause an additional 250,000 deaths per year from malnutrition, malaria, diarrhea and heat stress (WHO, 2015). (WHO, 2015).

Future projections show that mortality associated to temperature increase will be one of the most likely impacts on the health sector (IPCC, 2014; GASPARRINI et al., 2017). All in all, human beings have an ideal internal temperature range to maintain systemic homeostasis, but environmental exposure to extreme temperature conditions may exceed the human body's ability to maintain thermoregulation leading to heat stress (HAVENITH; FIALA, 2015). This events account for direct and indirect impacts on human health, causing symptoms that may vary from headaches, mental and physical exhaustion to death, especially in vulnerable groups (COFFEL; HORTON; SHERBINI, 2018).

The indexes used to assess heat stress on the human body are based on establishing an absolute limit on combined metabolic heat transfer, in addition to air temperature, different variables such as relative air humidity, wind speed and solar radiation (HAVENITH; FIALA, 2015). Even though many countries have presented some indicators combining temperature and humidity, there is no universal method used to quantify thermal comfort Over 160 different heat stress indexes have been developed, including the *Wet-Bulb Globe Temperature* (WBGT), the most popular and more broadly used in military training, sports medicine and work environment (BUDD, 2008; HAVENITH; FIALA, 2015).

The WBGT is an empirical index derived from the weighted average of the globe temperature, the natural wet bulb temperature and the dry bulb temperature and can be calculated using these variables: temperature, air humidity, wind speed and solar radiation (LILJEGREN et al., 2008). This index' safety limits are based on studies of physiological responses considering different combinations of acclimatization and metabolic expenditure, for example, WBGT values above 32°C are highly stressful for outdoor exercises and are generally used in sports, military and occupational safety training (ISO7243,1989; KJELLSTROM, 2016).

With the global temperature increase, projections indicate heat stress intensification by the end of the century, with values of wet bulb temperatures – a more sensitive metric to variations in air humidity compared to the WBGT – exceeding the theoretical limits established for human tolerance, especially in tropical regions (COFFEL; HORTON; SHERBININ, 2017).

In these regions, extreme wet bulb temperature events may be twice the projected change for temperature alone, and by the end of the century approximately 4% of the population in South Asia may experience a maximum wet bulb temperature exceeding 35°C under scenario RCP8.5 (Representative Concentration Pathways), which corresponds to the scenario with a radiative forcing of 8.5 W/m² across the planet, with an increase of more than 4°C in the global average temperature by 2100 (COFFEL; HORTON; SHERBININ, 2017; IM; PAL; ELTHAIR, 2017).

In Brazil, not many studies have been conducted on heat stress impacts on morbidity and mortality, taking into consideration the different climate change scenarios. From this perspective, this study aimed at assessing the risk of exposure to heat stress conditions, their association and potential impact on mortality from cardiovascular and respiratory diseases in Brazilian capitals for warming levels of 1.5°C, 2.0°C and 4.0°C using the Eta-HadGEM2-ES downscaled climate model in RCP8.5.

2 METHODOLOGY

2.1 APPROACHES

The assessment of impacts related to heat stress on human health, according to future warming scenarios, was developed under two approaches:

1. ***Assessment of exposure risk*** to heat stress for human health by comparing exposure to WBGT estimated from simulations of the Eta-HadGEM2-ES downscaled climate model according to the RCP8.5 scenario at warming levels of 1.5°C, 2.0°C and 4.0°C;

2. ***Assessment of impacts*** related to heat stress on mortality from cardiovascular (for people aged ≥ 45 years) and respiratory (for people aged ≥ 60 years) diseases, at warming levels of 1.5°C, 2.0° and 4.0°C of Eta-HadGEM2-ES downscaled climate model for the RCP8.5 scenario.

2.2 STUDY AREAS

Exposure risk was assessed for the entire Brazilian territory and its impacts on human health due to heat stress were studied for all Brazilian capitals. In spite of being focused on capital cities, results were presented per Brazilian regions.

2.3 CLIMATE SCENARIO

Exposure risk was assessed for the entire Brazilian territory and capital cities using RCPs that are climate scenarios based on CO_2 emissions, according to four different levels of radiative forcing in W/m² by 2100. Even though RCPs encompass four emission scenarios, this work used RCP 8.5, which corresponds to a high emission scenario, due to a large population growth and a low technological mitigation level, and with radiative forcing of 8.5 W/m², with average global warming temperature above 4°C by 2100, in other words, the worst case scenario with total absence of CO_2 control measures (IPCC, 2013).

2.4 ENVIRONMENTAL DATA

In order to estimate the exposure-response curve, mean WBGT during the afternoon was used, calculated by data from the *Era-Interim do European Centre for Medium-Range Weather Forecasts (ECMWF)* model (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim) for the period 2000 to 2010. In order to assess future impact, temperature, relative air humidity, wind speed and short-wave solar radiation were used, projected by the Eta-Hadgem2-ES downscaled model, developed by the Brazilian Institute for Space Research (INPE, in the Portuguese acronym) (CHOU et al., 2014). Each variable of the model was calibrated separately, using the models described by Hempel et al. (2013) and Casanueva et al. (2019) with the WBGT index being calculated later.

2.5 WET-BULB GLOBE TEMPERATURE (WBGT)

This study used the WBGT indicator to measure heat stress. This indicator measures heat exposure that leads to tension in the human body, and consequently, represents a potential risk to human health. It is used to assess heat overload in work activities both in indoor and outdoor environments. Maximum WBGT for outdoor environments was calculated by the following equation:

$$WBGT= 0\ 7Tw + 0,2Tg + 0.,1Ta$$

Where: Tw represents wet bulb natural temperature, Tg represents the black globe temperature and Ta represents dry bulb or atmospheric temperature. Tw and Tg values were estimated from maximum temperature data, relative air humidity, wind speed and radiation, by the method developed by Liljegren et al. (2008), and recommended by Lemke e Kjellstrom (2012).

In order to assess human health exposure to heat stress, risk classification thresholds were established according to the recommended ranges for physical exercise for children, a group considered vulnerable, and for intense work activities without acclimatization (AMERICAN ACADEMY OF PEDIATRICS, 2000; ISO7243, 1989) (Table 1).

Table1 | Heat stress risks for human health.

Thresholds of the WGBT	*Risk categories*
< 24°C	**Low risk –** All activities allowed
24°C a 25.9°C	**Moderate risk –** Longer rest periods in the shade; enforce drinking every 15 minutes
26°C a 29°C	**High risk –** Stop activity of unacclimatized persons and other persons with high risk; limit activities of all others (disallow long-distance races, cut down further duration of other activities)
> 29°C	**Extreme risk –** Cancel all athletic activities; high risk for human health.

Source: Committee on Sports Medicine and Fitness, American Academy of Pediatrics. (2000) and ISO7243 (1989).

For the risk of exposure to heat stress conditions, the projection of the 90th percentile and the percentage of days in which the values of maximum daily WBGT exceeded the 90th percentile in the reference period was used. This percentage was calculated using the Eta-HadGEM2-ES Downscaled Climate Model standard calendar, with 360 days, that is, the percentage of days within a 360-day year on which the maximum WBGT values exceeded the 90th percentile from 1961–2005.

2.6 HEALTH OUTCOMES

Impacts of heat stress conditions on human health were measured considering the following outcomes: mortality from cardiovascular diseases (CAD) (for people aged ≥ 45 years) (ICD 10: I00 to I99); and mortality from respiratory diseases (RAD) (for people aged ≥ 60 years) (ICD 10: J99 to J99).

2.7 ANALYSIS OF HEAT STRESS IMPACTS ON HUMAN HEALTH

Impact of exposure to heat stress in mortality outcomes was conducted according to the method used by Gasparrini et al. (2017) which includes the estimate of the exposure-response curve between the mean afternoon WBGT and health outcomes, and the assessment of future impacts of exposure to heat stress on health outcomes, according to climate scenarios.

The estimate of the exposure-response curve between mean afternoon WBGT and outcomes was conducted in two phases. The first phase estimated the effects of exposure to the mean afternoon WBGT using the generalized linear model, with *quasi-poisson* distribution combining the distributed lag non-linear models (DLNMs). Exposure-response curve estimates were based on the accumulated effects of 21 days for deaths from respiratory diseases and 07 days for deaths from cardiovascular diseases. Because the WBGT is an indicator composed of humidity, wind speed and radiation, only weekdays were included in the model adjustment. Trend and seasonality adjustments were made by a cubic time spline, with 7 degrees of freedom per year. The nonlinear and lag effect was modeled using a cross base defined by a natural cubic spline for WBGT, with three nodes allocated at the 10th, 75th and 90th percentiles. Lag effect adjustment was 21 days, with 3 nodes for deaths from respiratory diseases, and 7 days with 2 nodes for mortality from cardiovascular diseases.

In the second phase, assessment and adjustment of heterogeneity among capital cities was carried out through a meta-regression, with the temperature range and the Social Vulnerability Index (SVI) provided by the Institute for Applied Economic Research (IPEA, in the Portuguese acronym). Then, the effects for WBGT were recentralized, thus estimating Relative Risks for values above 28°C (WBGT ≥ 28°C), with these curves being used to assess future impact. The heat stress condition was defined according to values established for physical exercise for children and intense work activities without acclimatization (AMERICAN ACADEMY OF PEDIATRICS, 2000; ISO7243, 1989). For the association studied, the estimated curves have a J, V or U shape that describe an excessive death risk above or below a range or a specific value of the studied exposure, defined as minimum mortality temperature or WBGT. Hence, deaths tend to decrease as exposure increases up to a certain threshold or interval, above which they increase again. For WBGT, with minimum mortality risk defined at 28°C, most capital cities present a J-shaped curve, especially capitals in the Center-Western, Southeastern and Southern regions.

Projections and quantification of future impacts for global warming levels (SWL) of 1.5ºC (2011-2040), 2.0ºC (2041-2070) and 4.0ºC (2071-2099) were conducted by the calculation of attributable fractions. Attributable fractions are measures of effect based on the **Relative Risk** (RR) that quantify the excess death associated with an exposure value, in other words, the conditions of heat stress, always in comparison to a reference value, which in this case is death risk focused on WBGT equal to 28°C.

In this phase, the exposure-response curve accumulated between WBGT and deaths caused by cardiovascular and respiratory diseases, estimated by BLUP, calculated in the second stage of the first phase, was extrapolated to the projected data. The exposure-response function is applied to a daily series of 365 days of future health outcomes, constructed using daily averages from 2000 to 2010. Hence, it is assumed that the future estimated exposure-response curve will maintain the shape, taking into account the trends observed in the models estimated by BLUP, and that the distribution of deaths will remain constant. Subsequently, the impact quantification was estimated in terms of the attributable fraction of the outcomes associated with exposure to WBGT above 28°C (WBGT> 28°C). Analyses were conducted in the R program (2017) by **dlnm** (GASPARRINI, 2011) and **mvmeta** (GASPARRINI; ARMSTROG; KENWARD, 2012) packages.

3 OUTCOMES AND ANALYSES

3.1 RISKS OF EXPOSURE TO HEAT STRESS CONDITIONS

In relation to the risk of exposure to heat stress conditions, Figure 1 shows an expansion of areas with extreme health risk, according to warming scenarios. With a global increase of 4.0°C of temperature, the 90th percentile of WBGT indicates that all Brazilian regions will present areas of high and extreme risk to human health due to heat stress conditions, especially in the Northern and Center-Western regions. If the percentage of days above the values of the 90th percentile of the reference period (1960-2005) is considered, then the Northern and Northeastern regions may experience exposure above the P90 of the reference period in more than 90% of the days of the year for warming of 4.0°C.

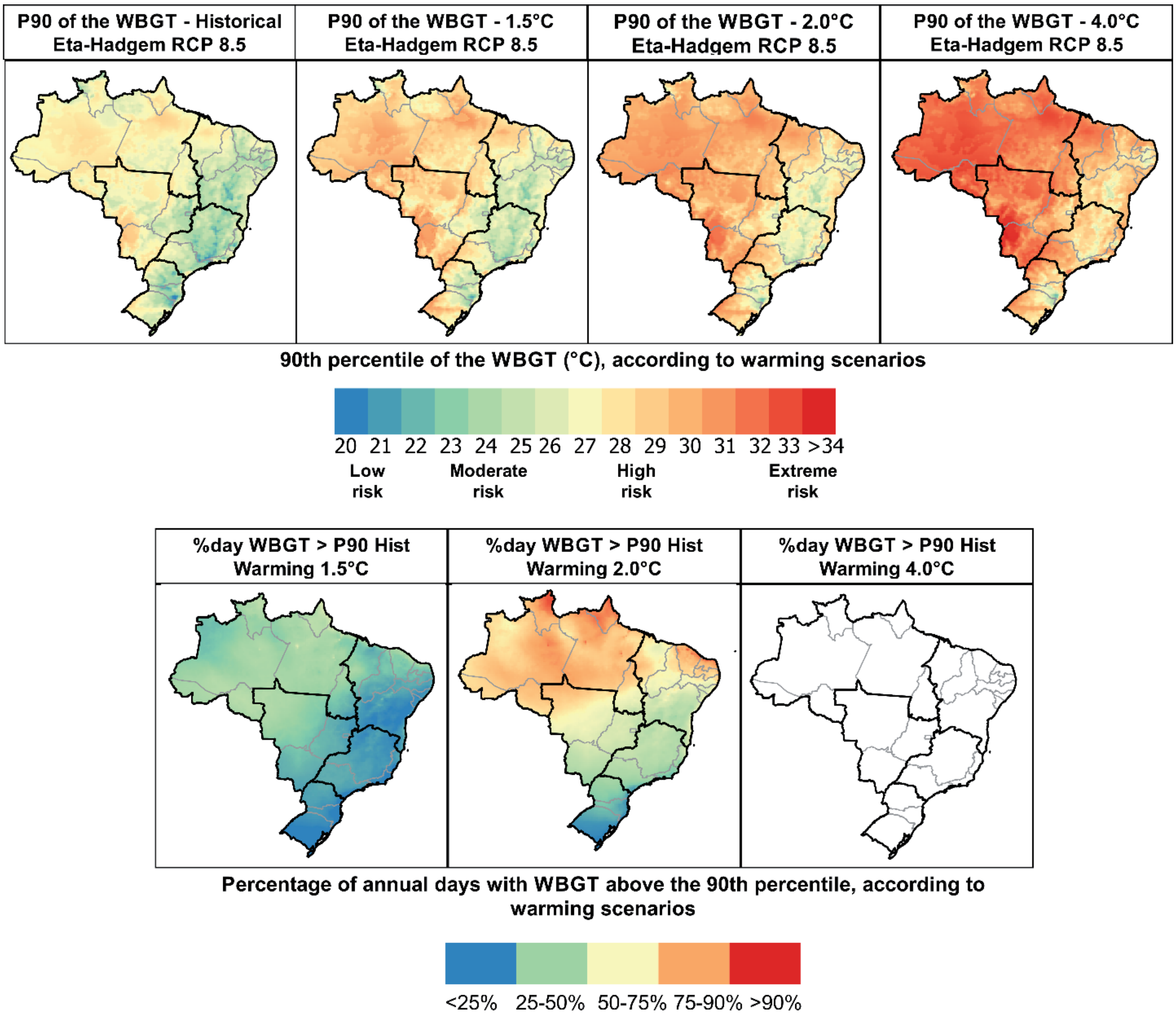


Figure 1 | 90th percentile of the Wet Bulb Globe Temperature (WBGT) heat stress indicator and Percentage of annual days with WBGT above the 90th percentile of the baseline period (1961-2005) according to warming scenarios for the Eta-Hadgem-ES climate model, RCP 8.5 scenario.

Source: Elaborated by the authors.

3.2 FUTURE IMPACTS OF HEAT STRESS CONDITIONS ON HUMAN HEALTH

The death toll from cardiovascular and respiratory diseases and the mean WBGT in the afternoon from 2000 to 2010 and for warming scenarios are shown in Table 2. Between 2000 and 2010, the Northern region presented the highest mean WBGT in the afternoon, especially Rio Branco, which reached a maximum value close to 34°C. Also, in the Northern region, there is an increase by approximately 5°C in the mean WGBT values in the afternoon for a global warming of 4°C.

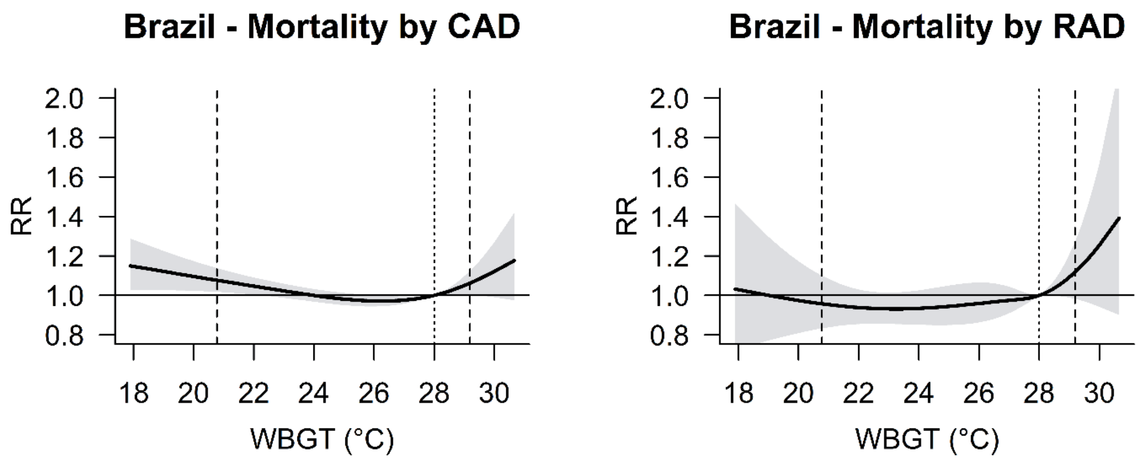
Table 2 | Death toll from cardiovascular (CAD) in adults aged over 45, and respiratory diseases (RAD) in the elderly above 60, daily average values of the *Wet-bulb Globe Temperature* (WBGT) during the afternoon from 2000 to 2010 and their respective averages for the projections, according to global warming scenarios.

Capital / region	*Death (2000 – 2010)*		*WBGT °C (2000-2010)*		*Global warming (Average WBGT)*			
	RAD	*CAD*	*Average*	*Min-Max*	*Baseline*	*1.5ºC*	*2.0ºC*	*4.0ºC*
NORTHERN								
Belém	7502	18803	28.2	23.9 - 31.5	27.7	29.1	30.4	32.3
Boa Vista	459	2146	28.0	23.2 - 31.5	27.5	28.7	30.0	31.3
Macapá	670	2323	27.7	24.1 - 30.4	27.0	28.6	30.1	31.9
Manaus	4508	13849	28.5	21.6 - 32.6	27.8	29.4	30.9	32.7
Palmas	233	1298	27.6	22.3 - 32.2	27.1	28.4	29.8	31.1
Porto Velho	1080	4113	28.5	17.6 - 32.1	27.8	29.5	31.0	32.8
Rio Branco	1239	2997	28.2	13.6 - 33.5	27.5	29.3	30.6	32.5
NORTHEASTERN								
Aracaju	2104	7634	25.9	22.2 - 29.7	25.6	26.7	27.9	29.3
Fortaleza	9020	29810	26.6	23.7 - 28.9	26.1	27.2	28.4	29.8
Joao Pessoa	3050	11618	25.9	22.9 - 28.7	25.5	26.7	27.9	29.2
Maceió	3808	15382	25.7	21.7 - 29.1	25.4	26.5	27.7	29.1
Natal	3144	12061	26.1	22.8 - 29.0	25.7	26.8	28.1	29.4
Recife	8843	33018	25.6	22.1 - 28.6	25.2	26.3	27.5	28.8
Salvador	11030	37751	25.6	21.2 - 30.3	25.3	26.6	27.8	29.2
São Luís	2442	12523	27.3	23.5 - 29.1	26.9	28.0	29.3	30.9
Teresina	2664	13512	28.4	23.4 - 32.7	28.0	29.2	30.5	31.9
CENTER-WESTERN								
Brasília	6034	28869	23.9	17.0 - 29.0	23.6	24.9	26.2	27.7
Campo Grande	3641	13156	25.2	8.10 - 30.9	24.6	26.3	27.6	29.3
Cuiabá	1964	7544	27.6	13.3 - 32.6	27.0	28.6	29.9	31.4
Goiânia	5870	19058	24.7	16.9 - 29.8	24.3	25.8	27.1	28.6
SOUTHEASTERN								
Belo Horizonte	11395	39896	23.2	14.6 - 30.7	22.7	24.2	25.5	27.1
Rio de Janeiro	49332	157405	24.6	14.5 - 31.3	24.2	25.6	26.5	28.1
São Paulo	66373	232329	22.2	10.1 - 29.8	21.6	23.4	24.5	26.2
Vitoria	802	4972	24.7	17.1 - 30.7	24.4	25.6	26.7	28.2
SOUTHERN								
Curitiba	7840	30667	21.2	4.70 - 30.6	20.6	22.4	23.5	25.1
Florianópolis	1463	5698	21.7	10.4 - 30.4	21.4	22.5	23.2	24.6
Porto Alegre	8735	34627	21.1	6.30 - 23.0	20.3	22.0	22.7	24.3

Source: Elaborated by the authors.

EXPOSURE-RESPONSE CURVE ESTIMATE

Figure 2 shows exposure-response curves between WBGT and mortality from cardiovascular and respiratory diseases combined for Brazil, by a meta-analysis. For cardiovascular diseases, a distribution of RR in a U-shaped format is observed, with a rise at both ends of the WBGT distribution. For WBGT values at P99 (~ 29.5°C), the RR accumulated in 7 days was about 15% higher compared to the RR observed for WBGT values at 28°C. The mortality curve from respiratory diseases was J-shaped, with an RR increase only for WBGT values above 28°C, where the accumulated RR in 21 days was 1.40 for WBGT ~31°C compared to RR for WBGT values at 28°C.



Caption: Relative risk (RR). The shaded area represents the 95% confidence interval, the dashed lines indicate the 1st and 99th percentiles of the afternoon WBGT, the dotted line represent the recentralization of the WBGT values curve above 28°C.

Figure 2 | Exposure-response curves between *Wet-bulb Globe Temperature (WBGT)* and cardiovascular disease mortality in adults aged over 45 and respiratory disease mortality in the elderly aged over 60 accumulated, respectively, in 7 and 21 days in Brazilian capital cities combined (2000 to 2010).

Source: Elaborated by the authors.

RR between the 99th percentile of the mean *WBGT* in the afternoon and mortality from cardiovascular and respiratory diseases compared to the risk of WBGT centered at 28°C for Brazilian capital cities is presented in Table 3. For some capitals, the 99th percentile of WBGT was lower or very close to the minimum RR adopted (risk in the WBGT equal to 28°C) and, therefore, the RR was close to or equal to 1 for both outcomes.

However, some capital cities stand out for presenting a death RR for the two outcomes in the 99th percentile of the WBGT in relation to the minimum RR adopted. In the Northern region, Palmas and Porto Velho presented an increment by 34% (IC95% 0.69 – 2.63) and 25% (IC95% 0.64 – 2.46), respectively, for deaths from RAD, and 19% (IC95% 0.81 – 1.76) and 23% (IC95% 0,85 – 1,79), respectively, for deaths from CAD. In the Center-Western region, Cuiabá stands out with an RR of 1.31 (IC95% 0.70 – 2.45) for RAD and 1.44 (IC95% 1.04 – 1.99) for CAD; in the Southeastern region, Rio de Janeiro stands out with an RR of 1.24 (IC95% 0.94 – 1.65) for RAD and 1.37 (IC95% 1.21 – 1.55) for CAD; in the Southern region, Porto Alegre stands out with an RR of 1.51 (IC95% 1.22 – 1.86) for RAD and 1.21 (IC95% 1.10 – 1.33) for CAD.

Table 3 | Relative risk between the *Wet-bulb Globe Temperature* (WBGT) in the 99th percentile in relation to WGBT at 28°C and cardiovascular disease mortality in adults aged over 45 and respiratory disease mortality in the elderly aged over 60 accumulated, respectively, in 7 and 21 days in Brazilian capital cities (2000 a 2010).

	99th percentile of the WBGT	*RAD (RR to P99 of the WBGT)*			*CAD (RR to P99 of the WBGT)*		
		CI95%			*CI95%*		
		RR	*Lower*	*Upper*	*RR*	*Lower*	*Upper*
NORTHERN							
Belém	29.9	1.17	0.73	1.87	1.00	0.79	1.27
Boa Vista	30.3	1.15	0.66	2.02	1.08	0.79	1.48
Macapá	29.3	0.95	0.59	1.54	1.02	0.78	1.33

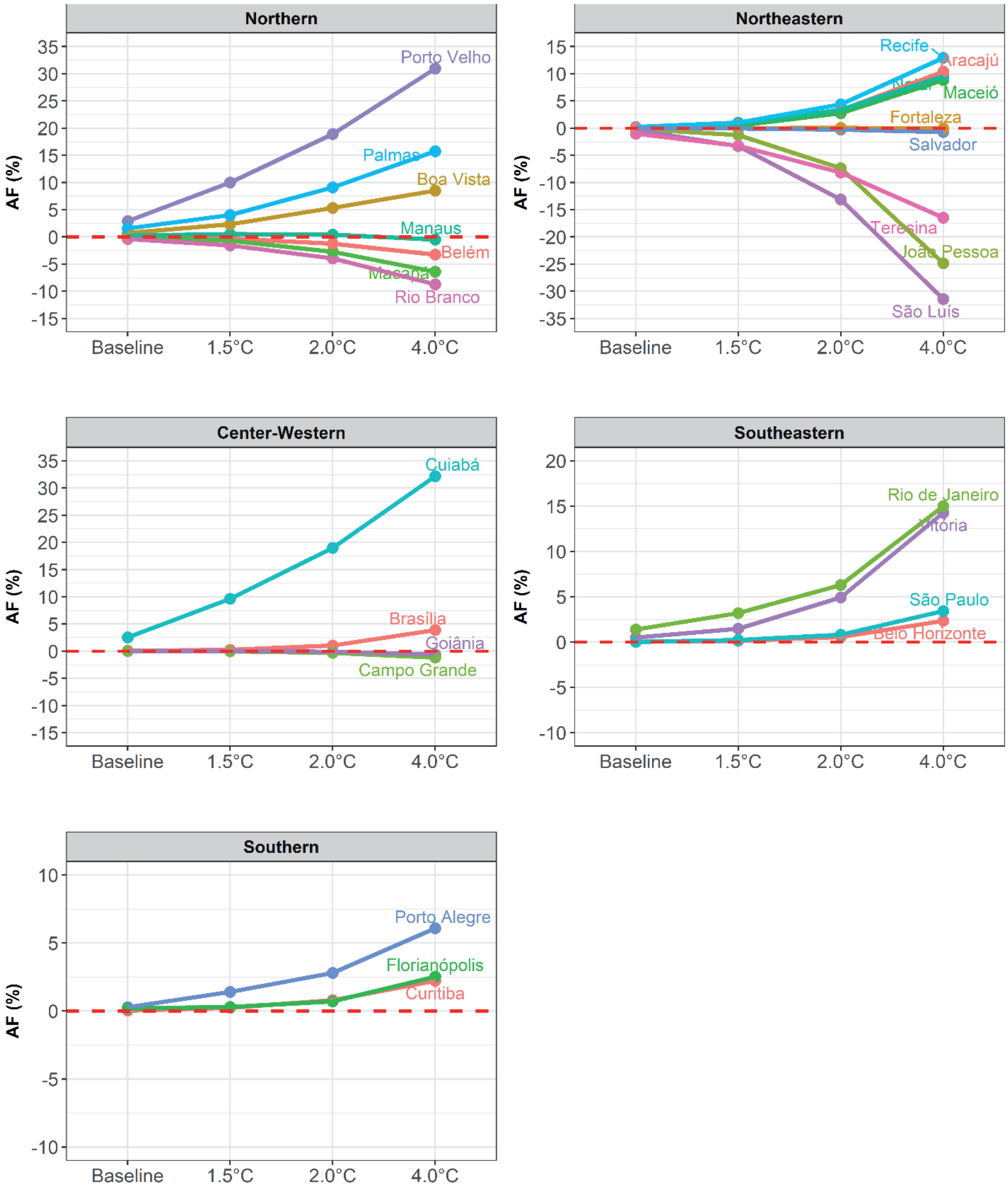
	99th percentile of the WBGT	RAD (RR to P99 of the WBGT)			CAD (RR to P99 of the WBGT)		
			CI95%			CI95%	
		RR	Lower	Upper	RR	Lower	Upper
Manaus	31.2	0.99	0.50	1.94	1.03	0.75	1.41
Palmas	31.1	1.34	0.69	2.63	1.19	0.81	1.76
Porto Velho	31.1	1.25	0.64	2.46	1.23	0.85	1.79
Rio Branco	31.4	1.13	0.64	2.00	0.97	0.68	1.39
NORTHEASTERN							
Aracaju	28.5	0.99	0.84	1.16	1.04	0.94	1.15
Fortaleza	28.2	1.01	0.94	1.09	0.99	0.94	1.04
Joao Pessoa	27.8	1.00	0.98	1.01	1.00	0.99	1.01
Maceió	28.1	1.00	0.94	1.06	1.01	0.97	1.04
Natal	28.1	1.00	0.94	1.07	1.01	0.97	1.05
Recife	27.8	1.00	0.93	1.08	0.98	0.94	1.03
Salvador	28.4	1.01	0.92	1.12	1.00	0.95	1.04
São Luís	28.7	1.00	0.70	1.43	0.96	0.78	1.18
Teresina	31.0	1.00	0.54	1.84	0.95	0.71	1.27
CENTER-WESTERN							
Brasília	27.2	0.91	0.68	1.23	0.99	0.87	1.12
Campo Grande	29.8	1.23	0.81	1.87	1.01	0.77	1.33
Cuiabá	31.2	1.31	0.70	2.45	1.44	1.04	1.99
Goiânia	28.3	1.07	0.96	1.18	1.02	0.97	1.07
SOUTHEASTERN							
Belo Horizonte	28.7	0.98	0.94	1.02	0.99	0.97	1.00
Rio de Janeiro	29.9	1.24	0.94	1.65	1.37	1.21	1.55
São Paulo	27.9	0.99	0.97	1.00	0.99	0.99	1.00
Vitoria	28.7	1.11	0.92	1.33	1.10	0.99	1.22
SOUTHERN							
Curitiba	28.2	1.02	0.97	1.06	1.01	0.99	1.02
Florianópolis	28.8	1.13	0.87	1.46	1.11	0.98	1.27
Porto Alegre	29.3	1.51	1.22	1.86	1.21	1.10	1.33

Source: Elaborated by the authors.

FUTURE IMPACTS OF EXPOSURE TO HEAT STRESS

For all health outcomes, as the level of global warming increases, the greater the number of deaths due to heat stress conditions in most capitals. However, the impacts differ depending on the location and the assessed outcomes. Impacts were measured by the attributable fraction (%) that corresponds to the percentage of deaths linked to an increase in WBGT.

In relation to deaths from cardiovascular diseases, a global warming of 4.0°C might have a positive impact on deaths from heat stress, with an attributable fraction lower than 5% for Brasília, Belo Horizonte, Curitiba, Florianópolis and São Paulo. Among the most impacted capital cities in terms of deaths from cardiovascular diseases are Palmas, Cuiabá and Porto Velho, with attributed fraction estimated above 30%. In the last two capitals, the attributable fraction increments to the scenario of greater warming compared to the baseline period are 26% and 28%, respectively (Figure 3).

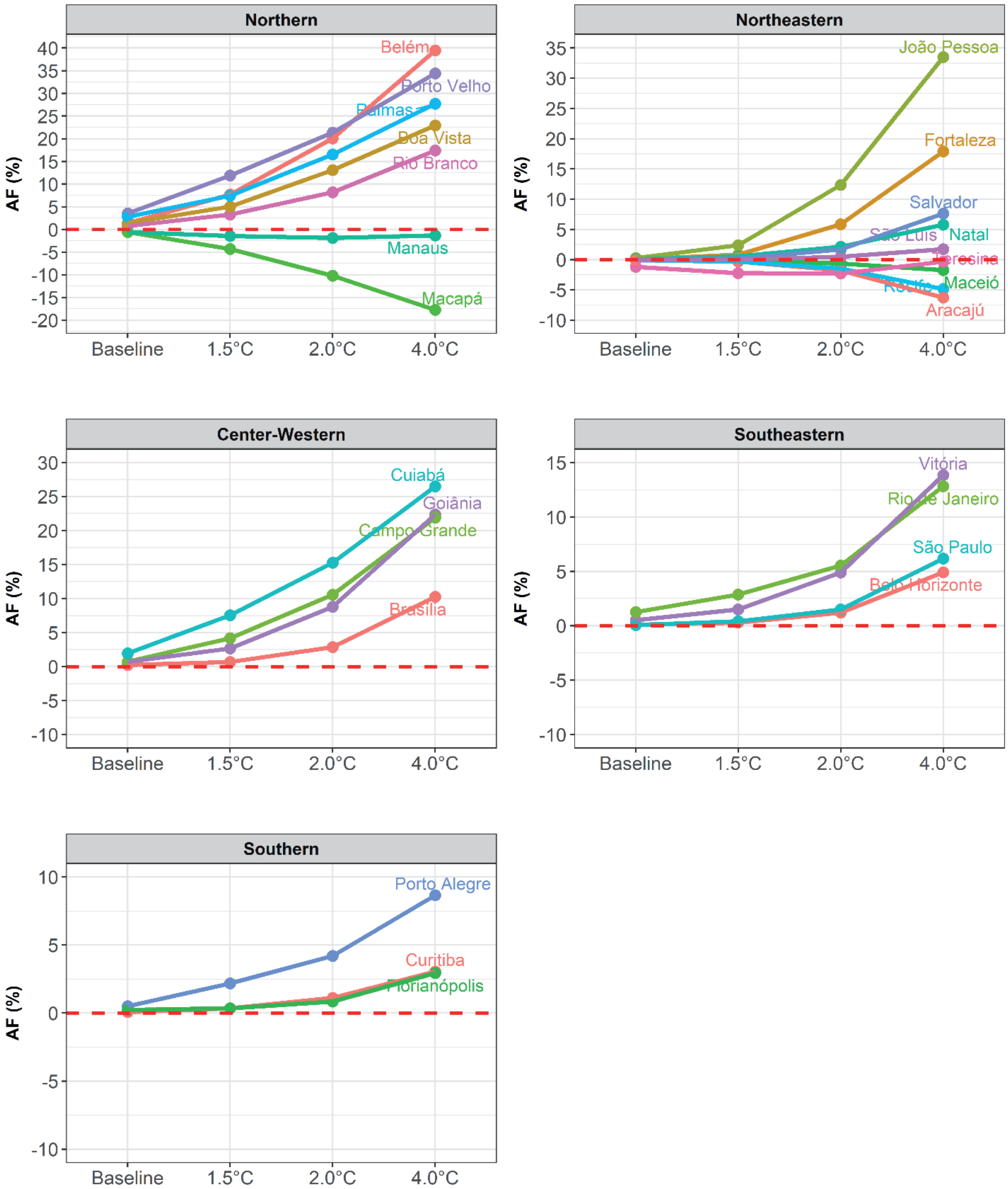


Caption: AF (%) Attributable fraction that measures how much of the outcome is attributable to exposure, that is, out of the total future deaths projected, which fraction (%) will be attributable to heat stress.

Figure 3 | Fraction of mortality from cardiovascular diseases (CAD) attributable to heat stress conditions (WBGT> 28°C) for the capital cities in the baseline period (1961-2005) and for warming scenarios of the Eta-Hadgem-ES (RCP 8.5) climate model.

Source: Elaborated by the authors.

In relation to deaths from cardiovascular diseases, a global warming of 4.0°C might represent an increased impact on deaths from heat stress in a number of capital cities. In the Northern region, the attributable fraction will gradually increase, according to warming levels for Belém, Porto Velho, Palmas, Boa Vista and Rio Branco, with Belém standing out with attributable fraction projections of 40% if the warming level is 4.0°C. In the Northeastern region, João Pessoa, Fortaleza, Salvador and Natal may have an increase in deaths from heat stress, especially João Pessoa with 35% of the attributable fraction of deaths related to heat stress. In the Center-West region, projections show every capital city will be impacted, with Cuiabá standing out with the highest attributable fraction: 25% for a warming level of 4.0°C. In the Southeastern region, Rio de Janeiro and Vitória present attributable fractions above 10% for a warming level of 4.0°C, and in the Southern region, Porto Alegre stands out with 7,5% (Figure 4).



Caption: AF (%) Attributable fraction that measures how much of the outcome is attributable to exposure, that is, out of the total future deaths projected, which fraction (%) will be attributable to heat stress.

Figure 4 | Fraction of mortality from cardiovascular diseases (CAD) attributable to heat stress conditions (WBGT> 28°C) for the capital cities in the baseline period (1961-2005) and for warming scenarios of the Eta-Hadgem-ES (RCP 8.5) climate model.

Source: Elaborated by the authors.

4 DISCUSSION AND CONCLUSION

This study showed projections on the risk of exposure to heat stress conditions for Brazil. The most striking impact projections were for the Northern and Center-Western regions, which may present extreme risk exposure for human health. In addition, results show a connection between WBGT and mortality from cardiovascular and respiratory diseases in Brazilian capital cities, especially Palmas, Porto Velho, Cuiabá, Rio de Janeiro and Porto Alegre in relation to impacts, projections indicate an upward trend as warming levels increase, although with heterogeneous results among capital cities.

Considering warming levels, if the RCP8.5 scenario is confirmed, practically all Brazilian regions will present an increase in heat stress conditions indicating risks for work (KJELLSTROM; HOLMER; LEMKE, 2009) and sports activities (NASSIS et al., 2015; LEYK et al., 2019). These risks have been reported in previous studies by Leyk at al. (2019). In 2014, during the World Cup, athletes' performance was impaired with WBGT values between 28 to 30°C, while two games were interrupted due to WBGT peaks above 30°C (NASSIS et al., 2015).

This study shows that at a warming level of 4.0°C, these situations might become more frequent, especially in the Northern and Center-Western regions. It is likely that warming and cooling intervals can be established and extended for various sports, as it has been done for tennis tournaments (TENNIS AUTRALIA LIMITED, 2019) and during the 2014 World Cup (LUCENA et al., 2017).

Regarding workers' health, work regimes that require body cooling are already regulated, for example, in the steel, glass and ceramics industries (ISO 7243, 1989). However, in some industries where exposure and prevention measures are not formally regulated yet, such as in agriculture, high rates of heat-related diseases have been reported (LUCAS; EPSTEIN; KJELLSTROM, 2014). The high risk of heat stress was observed among sugarcane cutters, who showed significant physiological changes, including changes in heart rate, body temperature and systolic blood pressure (BOONRUKSA et al., 2020). In Brazil, thermal overload, caused by intense work and exposure to high temperatures and humidity, was suggested as a triggering factor for the death of 14 sugarcane cutters between 2004 and 2008, in the state of São Paulo (BITENCOURT; RUAS; MAIA, 2012). In addition, heat stress risk has also been reported in civil construction activities (AL-BOUWARTHAN et al., 2019) and outside Brazil, for migrant workers from Nepal in Qatar (PRADHAN et al., 2019).

In more critical situations, occupational exposure beyond the established limits, associated with strenuous work, may be fatal. From 2000 to 2016, the Center for Disease Control and Prevention (CDC) retrospectively reviewed 25 occupational illnesses related to heat stress, with assessment of individual risk factors, exposure to WBGT, workload and acclimatization. Out of the 25 occupational hazards reviewed, exposure limits based on WBGT were exceeded for 14 fatal occupational diseases and 8 out of 11 non-fatal diseases. These results, associated with the results presented herein, reinforce the need for acclimatization programs, training and recognition of signs and symptoms needing first aid (TUSTIN et al. 2019).

Before the SARS-CoV-2 pandemic, estimates by the International Labor Organization (ILO) pointed that the effects of heat and heat stress could be responsible for the loss of 2.2% of global working hours, which would be equivalent to 80 million full-time jobs. In Brazil, estimates for 2030, with a warming level of 1.5°C, would be around 850 thousand jobs lost due to heat stress (ILO, 2019). This work's results show that a drop in work performance may be more pronounced for categories with high metabolic expenditure and rural communities and, therefore, new occupational health initiatives and strategies should be designed and implemented (KJELLSTROM; HOLMER; LEMKE, 2009; TUSTIN et al., 2019).

Results presented herein show that heat stress risk increases according to warming level and confirm other projections (IM; PAL; ELTHAIR, 2017; ANDREWS et al., 2019). In relation to the global population exposed, with a warming level of 1.5°C, the impact will be about 350 million people with compromised thresholds for work activities; whereas with a warming level of approximately 2.5°C, this exposure could reach more than 1 billion people (ANDREWS et al., 2019). Adaptation to extreme heat conditions will require options for active cooling, such as increased demand for air conditioning and changes to the work regime and sports activities and, in the absence of resources for adaptation, may generate waves of migration (MUELLER; GRAY; KOSEC, 2014).

Impact projections of heat stress conditions on mortality are notably sensitive to a number of behavioral and cultural factors that influence long-term physiological adaptation capacity (COLLIER et al., 2019). Perhaps this is one of the main bottlenecks in studies on the potential effects of heat on mortality: to predict or incorporate in the models the conditions and determinants of the health-disease process. When it comes to resilience, the globally economically active population is more sedentary, aging and with high rates of chronic diseases. These factors may reduce this group's thermal resilience and increase their susceptibility to heat-related illness (LOZANO et al., 2010).

In addition to working age adults, the elderly and children are considered to be at high risk for heat stress due to the limited ability to maintain body temperature and greater risk of dehydration (KENNY et al., 2010; GOMES; CARNEIRO-JÚNIOR; MARINS, 2013). Among children, the higher production of metabolic heat per unit of body mass and less sweating explain part of this vulnerability (BAR-OR, 1989; KENNY et al., 2010). Among the elderly, besides previous illnesses, thermal regulation is altered by reduced cellular metabolism and skin changes (KENNEY et al., 1997; INBAR et al., 2004).

Some capital cities analyzed in the present study showed an exposure-response curve for decreasing mortality, especially in places that experienced high WBGT values, such as the capitals in the Northern and Northeastern regions. These results suggest that a protective behavior might be adopted in response to extreme heat stress conditions or that these locations experience lesser effects. This lower sensitivity to the effects of heat in warmer regions has already been suggested by some authors (BASU, 2009; ZHAO et al., 2017; 2019). In any case, in some capital cities such as Palmas, Cuiabá and Porto Velho, which are known in the country for their high temperature records, there has been an increase in mortality from cardiovascular diseases attributable to heat stress, reaching a fraction attributed above 30% with a warming level of 4.0°C.

In Brazil, due to their cultural, socioeconomic, ecological and climate heterogeneity, impacts are likely to be associated with socioeconomic, individual and collective vulnerability issues, such as age, access to health services, physiological resilience and other social determinants, such as income and housing conditions (MARANDOLA; HOGAN, 2009). In densely populated regions, like the Southeast and South, some capitals may have a mortality rate that is attributable to heat stress above 10%, representing a significant impact on the absolute number of deaths. While in the Northern and Center-Western regions, despite the high attributable fraction, impact on absolute numbers might be lower. In any case, the Northern region presents high socioeconomic vulnerability and poor access to health services, with precarious conditions to face the impacts resulting from climate change (HACON et al., 2015).

Health service challenges are likely to be more extensive and complex than projections made. Projections point at an increment of climate-related disease burden, with chronic and infectious diseases overlapping. Hence, the increase in mortality from cardiovascular and respiratory diseases due to climate change will occur in a scenario in which other infectious disease increase, such as vector or water-borne diseases. Another aggravating factor will be the exacerbation of diseases associated with the effects of air pollution, especially in areas with advanced deforestation, which are associated with the spread of old and new pathogens. (FLOSS; BARROS, 2019). This is not a distant reality, as in 2020 Brazil experienced heat waves, increased fires and deforestation simultaneously, which are all environmental exposures associated with morbidity and mortality from chronic diseases combined with cardiovascular and respiratory diseases, and with the influence on the spread of old and new diseases, such as vector-borne ones.

Studies on future impacts of increased temperatures and heat stress are endowed with limitations and uncertainties. The 28°C threshold for WBGT, although pre-established by regulatory frameworks, may be underestimating the impacts of heat stress events due to socioeconomic and demographic conditions, access and quality of health services and the ability to adapt individuals (PARSONS, 2003, CUI et al., 2005).

Moreover, projections were made assuming a static baseline scenario for countless factors that could influence mortality, such as population growth, medical technologies, life expectancy and geographic distribution. Future climate conditions may have an influence on the adoption of new behaviors, due to the direct or indirect need of populations to adapt to new climate conditions. Therefore, new lifestyles, daily practices and eating habits may be modified, resulting in new nosological profiles and, consequently, influencing mortality from cardiovascular and respiratory diseases.

Despite all limitations and uncertainties, this study red-flags potential risks for mortality increase due to heat stress conditions should greenhouse gas emissions continue at the current pace. Projections point at important trends for Brazil, with the identification of high-risk areas for mortality from cardiovascular and respiratory diseases and implications for the country's global and occupational health.

REFERENCES

AL-BOUWARTHAN, M. et al. Heat Stress Exposure among Construction Workers in the Hot Desert Climate of Saudi Arabia. **Annals of Work Exposures and Health**, v. 63, p. 505-520, 2019.

AMERICAN ACADEMY OF PEDIATRICS. Committee on Sports Medicine and Fitness. Pediatrics. Climatic heat stress and the exercising child and adolescent. [Internet]. v. 106, 2000. Disponível em: <http://www.ncbi.nlm.nih.gov/pubmed/10878169>.

ANDREWS, O. et al. Implications for workability and survivability in populations exposed to extreme heat under climate change: a modelling study. **The Lancet Planetary Health**, v. 2, p. E540-E547, 2019.

BAR-OR, O. Temperature regulation during exercise in children and adolescent. In: LAMB, D. R.; GISOLFI, C. V. **Perspectives in exercise science and sports medicine:** youth, exercise, and sport. Indianapolis: Benchmark Press. p. 335-68, 1989.

BASU, R. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. **Environmental Health**, v. 8, 2009.

BITENCOURT, D. P.; RUAS, A. C.; MAIA, P. A. Análise da contribuição das variáveis meteorológicas no estresse térmico associada à morte de cortadores de cana-de-açúcar. **Cadernos de Saúde Pública**, v. 28, p. 65-74, 2012.

BOONRUKSA, P. et al. Heat Stress, Physiological Response, and Heat-Related Symptoms among Thai Sugarcane Workers. **International Journal Environmental Research and Public Health**, v. 17, p. 6363, 2020.

BUDD, G. M. Wet Bulb Globe Temperature (WBGT) – its history and its limitations. **Journal of Science and Medicine in Sport**, v.11, p. 20-32, 2008.

CASANUEVA, A. et al. Climate projections of a multivariate heat stress index: the role of downscaling and bias correction. **Geoscientific Model Development**, v. 12, p. 3419-3438, 2019.

CHOU, S. C. et al. Evaluation of the Eta Simulations Nested in Three Global Climate Models. **American Journal of Climate Change**, v. 3, p. 438-54, 2014.

COFFEL, E. D.; HORTON, R. M.; SHERBININ, A. Temperature and humidity-based projections of a rapid rise in global heat stress exposure during the 21st century. **Environmental Research Letters**, v. 13, p. 14001, 2018.

COLLIER, R. J. et al. Heat stress: physiology of acclimation and adaptation. **Animal Frontiers**, v. 9, p. 12-19, 2019.

CUI, J. et al. Effects of heat stress on thermoregulatory responses in congestive heart failure patients. **Circulation**, v. 112, p. 2286-92, 2005.

FLOSS, M.; BARROS, E. Lancet Countdown: briefing para políticas de saúde no Brasil. **Revista Brasileira de Medicina de Família e Comunidade**, v. 14, p. 2286, 2019.

GASPARRINI, A. Distributed Lag Linear and Non-Linear Models in R: the package dlnm. **Journal of Statistical Software**, v. 43, p. 1-20, 2011.

GASPARRINI, A. et al. Projections of temperature-related excess mortality under climate change scenarios. **The Lancet Planetary Health**, v. 1, p. e360-e367, 2017.

GASPARRINI, A.; ARMSTRONG, B.; KENWARD, M. G. Multivariate meta-analysis for non-linear and other multi-parameter associations. **Statistics in Medicine**, v. 31, p. 3821-39, 2012.

GOMES, L. H. L. S.; CARNEIRO JÚNIOR, M. A.; MARINS, J. C. B. Respostas termorregulatórias de crianças no exercício em ambiente de calor. **Revista Paulista de Pediatria**, v. 31, p. 104-10, 2013.

HACON, S. et al. Vulnerabilidade, riscos e impactos das mudanças climáticas sobre a saúde no Brasil. In: **Terceira Comunicação Nacional sobre Mudanças Climáticas à UNFCC (TCN-UNFCC)**, 2015.

HAVENITH, G.; FIALA, D. Thermal Indices and Thermophysiological Modeling for Heat Stress. In: **Comprehensive Physiology.** Hoboken, NJ, USA: John Wiley & Sons, Inc. p. 255-302, 2015.

HEMPEL, S. et al. A trend-preserving bias correction – The ISI-MIP approach. **Earth System Dynamics**, v. 4, p.219-236, 2013.

IM, E-S.; PAL, J. S.; ELTAHIR, E. A. B. Deadly heat waves projected in the densely populated agricultural regions of South Asia. **Science Advances**, v. 3, p. e1603322, 2017.

INBAR, O. et al. Comparison of thermoregulatory responses to exercise in dry heat among prepubertal boys, young adults and older males. **Experimental Physiology**, v. 89, p. 691-700, 2004.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). **Climate Change 2014:** mitigation of climate change. New York, NY: Cambridge University Press, 2014.

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE (IPCC). **Climate Change: 2013:** the physical science basis. Summary for Policymakers. Geneva, Switzerland, 2013.

INTERNATIONAL LABOUR ORGANIZATION (ILO). **Working on a warmer planet:** the impact of heat stress on labour productivity and decent work. International Labour Office – Geneva, ILO, 2019.

INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO). **ISO Standard 7243**: ergonomics of the thermal environment – assessment of heat stress using the WBGT (Wet Bulb Globe Temperature) index. Disponível em: <https://www.iso.org/standard/67188.html>. Acesso em: 01 set. 2020.

KENNEY, W. L. et al. Decreased active vasodilator sensitivity in aged skin. **American Journal of Physiology-Heart and Circulatory**, v. 272, p. H1609-14, 1997.

KENNY, G. P. et al. Heat stress in older individuals and patients with common chronic diseases. **Canadian Medical Association Journal**, v. 182, p. 1053-60, 2010.

KJELLSTROM, T. Impact of climate conditions on occupational health and related economic losses: a new feature of global and urban health in the context of climate change. **Asia Pacific J Public Health**, v. 28, p. 28S-37S, 2016.

KJELLSTROM, T. et al. The direct impact of climate change on regional labor productivity. **Archives of Environmental & Occupational Health**, v. 64, p. 217-227, 2009.

LEMKE, B.; KJELLSTROM, T. Calculating workplace WBGT from meteorological data: a tool for climate change assessment. **Industrial Health**, v. 50, p. 2012.

LEYK, D. et al. Health Risks and Interventions in Exertional Heat Stress. **Deutsches Arzteblatt International**, v. 116, p. 31-32, 2019.

LILJEGREN, J. C. et al. Modeling the Wet Bulb Globe Temperature Using Standard Meteorological Measurements. **Journal of Occupational and Environmental Hygiene,** v. 5, p. 645-55, 2008.

LOZANO, R. et al. Global and regional mortality from 235 causes of death for 20 age groups in 1990 and 2010: a systematic analysis for the global burden of disease study 2010. **Lancet**, v. 380, p. 2095-2128, 2013.

LUCAS, R. A. I.; EPSTEIN, Y.; KJELLSTROM, T. Excessive occupational heat exposure: a significant ergonomic challenge and health risk for current and future workers. **Extreme Physiology & Medicine**, v. 3, p. 1-8, 2014.

LUCENA, R. L. et al. The Brazilian World Cup: too hot for soccer? **International Journal of Biometeorology**, v. 61, p. 2195-2203, 2017.

MARANDOLA, J. R.; HOGAN, D. J. Vulnerabilidade do lugar vs. vulnerabilidade sociodemográfica: implicações metodológicas de uma velha questão. **Revista Brasileira de Estudos de População**, v. 26, p. 161-81, 2009.

MULLER, V.; GRAY, C.; KOSEC, K. Heat stress increases long-term human migration in rural Pakistan. **Nature Climate Change**, v. 4, p. 182-185, 2014.

NASSIS, G. P. et al. The association of environmental heat stress with performance: analysis of the 2014 FIFA World Cup Brazil. **British Journal of Sports Medicine**, v. 49, p. 609-13, 2015.

PARSONS, K. **Human Thermal Environments:** the effects of hot, moderate and cold environments on human health, comfort and performance. London and New York: Taylor & Francis, 2003.

PRADHAN, B. et al. Heat stress impacts on cardiac mortality in Nepali Migrant workers in Qatar. **Cardiology**, v. 143, p. 37-48.

TENNIS AUSTRALIA LIMITED. **AO Heat Stress Scale a Grand Slam first**. Disponível em: <www.ausopen.com/articles/news/ao-heat-stress-scale-grand-slam-first>. Acesso em: 01 set. 2020.

TUSTIN, A. W. et al. Evaluation of Occupational Exposure Limits for Heat Stress in Outdoor Workers – United States, 2011-2016. **MMWR Morb Mortal Wkly Rep**, v. 67, p. 733-737, 2019.

WORLD ORGANIZATION HEALTH (WHO). **Climate and Health Country Profiles – Brazil – 2015**. United Nations: Framework Convention on Climate Change, 2015.

WORLD ORGANIZATION HEALTH (WHO). **Ten threats to global health 2019**. Disponível em: <https://www.who.int/news-room/spotlight/ten-threats-to-global-health-in-2019>. Acesso em: 01 set. 2020.

ZHANG, Y. Diurnal Temperature Range in Relation to Daily Mortality and Years of Life Lost in Wuhan, China. **International Journal Environment Research and Public Health**, v. 14, p. E891, 2017.

ZHANG, Y. et al. The burden of ambient temperature on years of life lost: a multi-community analysis in Hubei, China. **Science Total Environment**, v. 621, p. 1491-1498, 2018.