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Heat waves: characterization, metrics and effects

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ABSTRACT
In the context of climate change, many efforts have been made to avoid or mitigate its effects. Extreme weather events such as heatwaves have become more frequent and intense worldwide, causing complications to human health, besides other environmental and socioeconomic imbalances. Thus, this article conducts a current bibliographical and documental review in order to define heatwaves, highlight the use of the Heat Index to quantify thermal perception, and evaluate their harmful effects. It was found that the greatest health risk occurs in the elderly and in individuals with weakened circulatory and respiratory systems. Other indirect consequences include insect proliferation, contamination of groundwater, changes in agricultural production, the need for adjustments in psychotropic and antihypertensive medication dosages, interruptions in transportation and power supply systems, and an increase in work accidents.
KEYWORDS: Heat waves. Climate change. Heat index. Extreme weather events. Mitigating actions.

1 INTRODUCTION

Constituting one of the central themes of the United Nations Sustainable Development Goals (SDGs), the issue of climate change currently represents a global concern, mainly due to the already observed harmful effects on the environment, economy, and society (UN, 2022a).

The emissions of greenhouse gases (GHGs) such as carbon dioxide (CO_2), ozone (O_3), methane (CH_4), and nitrous oxide (N_2O) have increased since the pre-industrial era, due to economic and population growth. The rise in the concentration of these gases in the atmosphere leads to an increase in terrestrial temperatures (MOREIRA; GIOMETT, 2008; IPCC, 2014). This contributes to the global phenomenon of climate change, changing rainfall patterns and altering the distribution of extreme events, characterized as a scenario of uncertainties and concerns (NOBRE, 2001; RIBEIRO, 2008; IPCC, 2014; ESPÍNDOLA; RIBEIRO, 2020).

Extreme weather events are defined as those with atypical duration, intensity, and/or frequency that cause damage to the functioning of a community or society in their daily lives. For example, one can cite the occurrence of heatwaves, droughts, wildfires, hurricanes, extreme cold, heavy precipitation, floods, landslides, among others (FIOCRUZ, 2022).

Nairn and Fawcett (2015) point out that heatwaves have historically caused more deaths in Australia, the United States, and Europe than any other natural disaster. The World Health Organization (WHO) highlights those deaths are usually indirectly related to heatwaves, as they tend to exacerbate existing health conditions such as diabetes, heart diseases, multiple sclerosis, and kidney problems, affecting the body's thermal and water regulation mechanisms (HAVENITH, 2005).

The strong heatwave that spread across Europe in 2022 was widely reported in international media. Countries such as the United Kingdom, Portugal, Spain, and France faced an extreme climate that required rapid and effective measures to minimize health damage to their residents.

The United Kingdom's Meteorological Service issued a red heat alert for the first time in its history in 2022. Thermometers in London recorded temperatures exceeding 40ºC, surpassing the previous national record of 38.7°C, which had been registered in Cambridge during the summer of 2019. Both the British agency and the World Meteorological Organization (WMO) attributed this phenomenon to climate change, emphasizing that increased frequency, duration, and intensity of heatwaves are directly linked to anthropogenic activities (UN, 2022b).

In July 2022, temperatures in Portugal and Spain reached staggering highs of 46ºC,

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leading to a series of significant wildfires across both nations. In France, the National Meteorological Service issued extreme heat alerts for 15 of its 96 administrative departments, with an additional 15 departments receiving an orange alert. The wildfires resulting from this extreme heat consumed over 13,000 hectares within five days in the Gironde region, with 7,300 hectares burned in a single day (UN, 2022b).

"It is evidently a fallacy to view this heatwave as a localized phenomenon exclusive to Europe. Extreme heat events have been occurring globally, particularly during the summer months of their respective hemispheres," asserts researcher Alexandre Costa (BBC, 2022).

Mazdiyasni et al. (2017) conducted a study whose results suggest that the number of deaths due to heatwaves is expected to increase substantially in the coming years in developing countries. In India, the location where the study was conducted, intense heatwaves will become two and a half times more frequent with an increase of half a degree in the country's average summer temperature, which was predicted by the researchers as inevitable.

In this context, research involving the analysis of international climate scenarios and aspects can and should be used as a parameter to obtain diagnoses and prognoses regarding the effects of heatwaves and how to mitigate them in the appropriate manner.

Thus, a benchmarking environment can be created that can be used in proposing methodologies for analyzing heatwaves, considering environmental and socioeconomic factors and thus contributing to the promotion of climate justice (TORRES et al., 2021).

Based on existing practices and models, it is possible to identify what can be adopted as a reference to improve metrics, processes, and/or strategies regarding heatwaves. It is a pedagogical process in which it is evaluated what can be incorporated from other agents and adapted for application in a specific context (MARQUES, 2021).

Given that Brazil lacks studies on heat waves (BEU, 2020), the integration of both external and internal knowledge and experiences is beneficial for establishing analytical parameters for these extreme events.

It is essential to highlight the need for this discussion and the expansion of such studies in Brazil, particularly since at the beginning of the 21st century, approximately 85% of the country's population resided in urban areas. This concentration is primarily evident in just nine metropolitan areas, home to 50 million people—more than the population of most countries in Europe or Latin America. Over the past 60 years, Brazil's urban population has increased by over 100 million individuals through an extremely violent and predatory process that has resulted in a built environment characterized by inequality and limited interaction with green spaces and the natural environment, particularly in self-constructed urban peripheries (MARICATO, 2015; MEIRELES, 2017).

In this context, the present article contributes by providing a current and comprehensive documentary and bibliographic review of the key topics related to heat waves, emphasizing their characterization, perception metrics, direct effects on human health, and socioeconomic and environmental impacts.

2 METHODOLOGY

This work presents an international bibliographic and documentary review regarding

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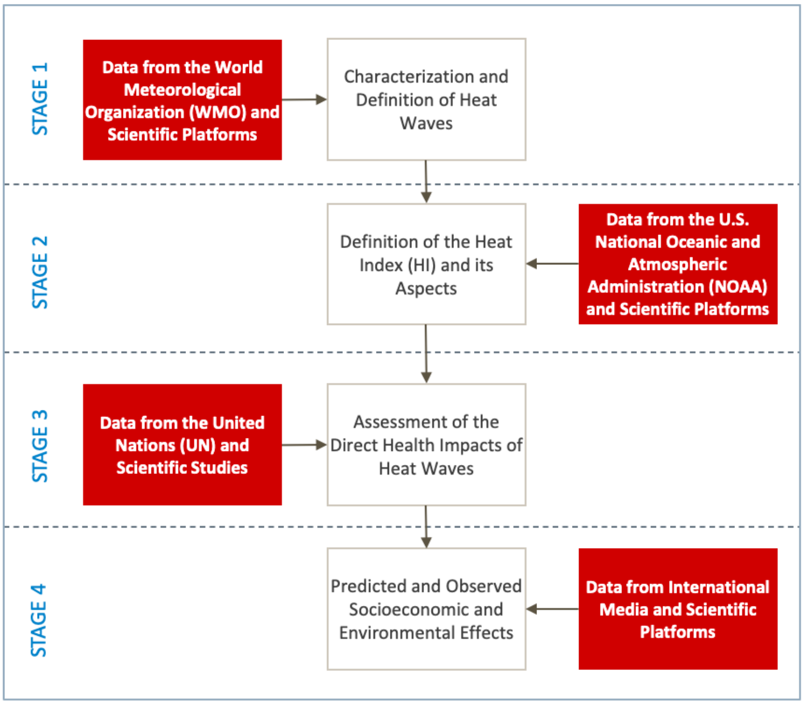
the phenomenon of heat waves and its relevant aspects. To achieve this, data were gathered from scientific publications related to the topic as well as from international institutions recognized for their work on climate and environmental issues.

The study procedures were divided into four main stages, each corresponding to one of the chapters of this article. Figure 1 illustrates the methodological flowchart that guided this research.

Figure 1 - Flowchart of methodological steps and procedures.



Source: The Authors (2022).

In Stage 1, the characterization of heat waves was conducted according to their primary authors through the discussion of their various definitions and aspects. Stage 2 provides a historical overview of the creation and use of one of the metrics developed to quantify heat perceived by human metabolism: the Heat Index (HI). In Stage 3, the harmful effects of heat waves on human health were examined, while Stage 4 presented the current socioeconomic and environmental effects resulting from these events.

3 CHARACTERIZATION OF HEAT WAVES

According to Hess et al. (2014) and Tasian et al. (2014), the demand for specific medical treatments and the number of hospital emergency visits are associated, among other factors, with the occurrence of elevated temperatures.

Furthermore, the study conducted by Xu et al. (2016) observed that heat waves significantly increase global human mortality. Additionally, the authors noted that the effects of these events on human health depend on the interpretation of the term "heat waves."

Diniz (2022) emphasizes that there is no universal definition of heat waves, as

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definitions often vary in terms of duration and intensity; however, he cites the parameters of three primary definitions:

(a) WMO (2001): According to the World Meteorological Organization (WMO), a heat wave can be defined as "when the daily maximum temperature over a period of at least five days exceeds the average maximum temperature by at least 5°C." Researchers, however, point out the limitations of this definition: the variation in temperature compared to what is normally observed may not necessarily indicate a heat wave depending on the region studied; furthermore, the duration of a heat wave does not necessarily need to exceed five days.

(b) Robinson (2001): This author defines a heat wave as a period of at least 48 hours during which the Heat Index (defined in Section 4 of this article), related to apparent temperature, remains above the thresholds set by the National Weather Service of the United States (105°F during the day and 80°F at night).

(c) Russo et al. (2014): These authors consider heat waves to be periods of at least three consecutive days during which maximum temperatures exceed the 90th percentile threshold of the maximum temperature considered typical for the reference period."

4 METRICS OF HEAT PERCEPTION IN HUMAN METABOLISM

One of the metrics utilized to assess the effects of heatwaves on human health is through biometeorological indices of human thermal perception, which vary in terms of objectives, variables considered, and sophistication. The study conducted by Freitas and Grigorieva (2014) enumerated 162 heat indices, each with its associated variables.

It is important to emphasize that the temperature perception of each individual can be influenced by psychological and behavioral factors (Lin; Dear; Hwang, 2011). Moreover, variables such as clothing and physical activity levels have a direct impact on how the human body perceives temperature (Mistry, 2020).

However, climatic and, consequently, environmental factors are primarily responsible for significant impacts on the understanding of human metabolism regarding perceived heat. McGregor and Vanos (2018) identify the main components influencing thermal sensation as air temperature, relative humidity, thermal radiation, and wind speed.

The authors note that heat dissipation through ventilation occurs when the air temperature is lower than an individual’s average body temperature, which is considered to be 36°C. This mechanism also affects the rates of evaporation from the skin to the atmosphere (McGregor & Vanos, 2018). Another study observed that wind direction also plays a significant role in the intensity of the urban heat island effect (Oliveira et al., 2021).

In developing an equation for a heat index that incorporates as many parameters as possible associated with human thermal perception, Steadman (1979) included factors such as human dimensions, effective skin radiation area, vapor pressure, effective wind speed, and radiation levels, among others.

However, the initial model had to be simplified to make its involved variables more conventional. The resulting Heat Index (HI), updated by Rothfusz (1990), ultimately retained only two independent variables, which represent strictly climatic factors: average dry air temperature and relative humidity (Silva et al., 2017).

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The decision to include relative humidity in the Heat Index formula is justified by its significance in the body's perception of ambient temperature, as it is directly related to the rate of skin evaporation, a mechanism utilized by metabolism for cooling (Christopherson, 2012). As air humidity increases, the sensation of discomfort due to heat and mugginess becomes more pronounced, as high concentrations of water vapor particles in the air hinder sweat evaporation (Basarin; Lukic; Matzarakis, 2020).

Dry air temperature is the primary element of thermal sensation, given that the human body is surrounded by atmospheric air. Maulbetsch (2010) points out that this factor must be incorporated in Equation 1 in degrees Fahrenheit, as the Heat Index in its most current form, as previously mentioned, was formulated by the National Oceanic and Atmospheric Administration (NOAA) of the United States, where this is the standard temperature measurement unit.

$$HI = c_1 + c_2.T + c_3.\varphi + c_4.T.\varphi + c_5.T^2 + c_6.\varphi^2 + c_7.T^2.\varphi + c_8.T.\varphi^2 + c_9.T^2.\varphi^2 \quad (1)$$

Variables in Equation 1:

HI - Heat Index (°F)

T - Dry air temperature (°F)

ϕ - Relative humidity (%)

Constants in Equation 1:

c_1 = - 42,379

c_2 = 2,049

c_3 = 10,143

c_4 = - 0,225

c_5 = - 6,838.10^{-3}

c_6 = - 5,482.10^{-2}

c_7 = 1,229.10^{-3}

c_8 = 8,528.10^{-4}

c_9 = - 1,99.10^{-6}

Rothfusz (1990) highlights that Equation 1 was derived through multiple regression analysis, and the resulting Heat Index value may exhibit an error margin of up to ±1.3°F.

NOAA (2022) notes that adjustments to the Heat Index equation are necessary when relative humidity is below 13% and air temperature falls within the range of 80°F to 112°F (26.7°C to 44.4°C). Another scenario requiring adjustments occurs when relative humidity exceeds 85% and air temperature is between 80°F and 87°F (26.7°C to 30.6°C). According to NOAA (2022), if temperature and humidity conditions result in a Heat Index below 80ºF (26.7ºC), the Rothfusz regression (1990) is deemed inappropriate for calculations. Instead, a simpler formula that aligns with Steadman's (1979) results is recommended. Nonetheless, there is currently an online tool available on NOAA's official website that directly computes the Heat Index based on the aforementioned factors, integrating these specificities into its calculations.

Figure 2 illustrates the variation of the Heat Index (in ºC) in relation to dry bulb temperature (in ºC) on the horizontal axis and relative humidity (in %) on the vertical axis.

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Figure 2 - Variation of IC with dry air temperature and relative air humidity.

	27	28	29	30	31	32	33	34	36	37	38	39	40	41	42	43
4	27	27	28	29	31	33	34	36	38	41	43	46	48	51	54	58
7	27	28	29	31	32	34	36	38	40	43	46	48	51	54	58	
10	27	28	29	31	33	35	37	39	42	45	48	51	55	58		
13	27	29	30	32	34	36	38	41	44	47	51	54	58			
16	28	29	31	33	35	38	41	43	47	51	54	58				
18	28	29	32	34	37	39	42	46	49	53	58					
21	28	30	32	35	38	41	44	48	52	57						
24	29	31	33	36	39	43	47	51	56							
27	29	32	34	38	41	45	49	54								
29	29	32	36	39	43	47	52	57								
32	30	33	37	41	45	50	55									
35	30	34	38	42	47	53										
38	31	35	39	44	49	56										

Source: The Authors (2022), adapted from NOAA (2022).

In Figure 2, each color signifies the level of danger to human health associated with the Heat Index values derived from temperature and humidity. The yellow color represents Level 1, where attention should begin to be exercised during prolonged physical activity, as the heat may lead to exhaustion. Level 2, depicted in orange, indicates an increased health risk, as harmful effects such as sunburns could become a concern. Dark orange, representing Level 3, indicates a heightened danger, as skin burns are likely with even brief sun exposure, and heat-related collapse may occur. Level 4, marked in red, characterizes a heatwave, during which all effects listed in Section 4 of this study may manifest (NOAA, 2022).

Table 1 outlines the characteristics associated with each of these danger levels linked to the variation of the Heat Index, emphasizing who is at risk and potential actions that may be taken in each scenario to minimize harm.

The so-called Level 0, where the health risk is low or even negligible, is not depicted in Figure 2, although it is included in Table 1, as it pertains to temperatures below 27ºC, the minimum value represented in the aforesaid figure.

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Table 1 - Aspects and danger levels of Heat Index variation

Danger Level	Meaning	What/Who is at risk?	How common is this heat in the US?	For those who are at risk, what actions can be taken?
0	Heat level with little or no risk to human health	No significant risk	Very common	Additional preventive actions should not be necessary
1	Heat level tolerated by most of the population, but with a low risk of health effects for heat-sensitive individuals	Primarily those who are extremely sensitive to heat	Very common	• Increase hydration level • Reduce time outdoors or stay in shaded areas when solar radiation is stronger • Open windows at night and use fans to cool indoor spaces
2	• Moderate risk of experiencing health effects for heat-sensitive individuals • Some risk for those exposed to the sun and performing some type of physical activity • For those without air conditioning, living spaces can be uncomfortable during the day.	• Mainly people sensitive to heat, especially in the absence of adequate refrigeration and hydration; • Partial risk for transport and essential sectors such as water supply and electricity	• Quite common in most regions of the country • Very common in the south of the country	• Reduce sun exposure time between 10am and 4pm • Stay hydrated • Stay in cool places during the heat of the day • Change the times of outdoor activities to cooler periods of the day • Open windows at night and use fans to cool indoor spaces and circulate air
3	• High risk for those who are exposed to the sun and perform some type of physical activity, in addition to those who are sensitive to heat • Dangerous to anyone without adequate refrigeration and hydration; • Air quality may be impaired • Interruptions in electricity supply may occur due to increased demand for refrigeration	• Majority of the population, especially those who are sensitive to heat and anyone without adequate cooling and hydration; • Increased risk for transport and essential sectors	• Uncommon in most northern locations • Quite common in southern regions	• Try to avoid exposure to the sun between 10am and 4pm • Stay hydrated • Stay in cool places, especially during the heat of the day • Using air conditioners, fans may be inappropriate • Canceling outside activities during the heat of the day
4	• Very high risk for the entire population • Very dangerous for those without adequate refrigeration and hydration • Characterizes heat wave • Poor air quality is likely • Probable blackouts in the electricity grid due to critical levels that demand may reach	• The entire population is at risk; • For those who are sensitive to heat, especially in the absence of adequate cooling and hydration, this level of heat can be deadly; • Increased risk for transport and essential sectors	• Rare in most locations • Occurs a few times a year in southern regions, especially in the southwestern deserts	• Avoid exposure to the sun between 10am and 4pm • Stay hydrated • Stay in cool places, even at night • Use air conditioners, fans will not be suitable • Canceling outside activities during the heat of the day

Fonte: Source: The Authors (2022), adapted from NOAA (2022).

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5 DIRECT EFFECTS OF HEAT WAVES ON HUMAN HEALTH

Humans are homeothermic and endothermic organisms, meaning they maintain a stable body temperature through metabolic processes. Two physiological mechanisms are crucial for reducing body temperature during extreme heat exposure: perspiration and peripheral vasodilation (DINIZ, 2022).

Perspiration involves the loss of water through sweat, which facilitates heat loss via evaporation. However, this thermoregulatory mechanism can lead to significant dehydration, as the body may lose up to 2 to 3 liters of water per hour (VOGELAERE; PEREIRA, 2005). Maulbetsch (2010) notes that for perspiration to be effective, ambient humidity must not be high enough to impede the evaporation process.

Peripheral vasodilation increases blood flow to the skin, resulting in heat loss through radiation and convection. However, this mechanism also leads to an increased heart rate to expedite circulation (HOUDAS; RING, 1982), which can strain both the respiratory and circulatory systems.

Thus, individuals with compromised respiratory and circulatory systems are more vulnerable to heat waves, particularly the elderly, due to their slower and less efficient thermoregulatory responses (HOUDAS; RING, 1982). According to Havenith (2005), the impacts of heat waves on human health can also vary based on factors such as socioeconomic conditions, the effectiveness of mitigation measures, the capacity of the healthcare system and its professionals, and the speed of intervention, among others. Laaidi et al. (2012) suggest that in urban areas, the risk of mortality from extreme temperatures is heightened due to the formation of heat islands.

Guo et al. (2018) emphasize that the aging Brazilian population necessitates the development and implementation of public policies focused on mitigation and adaptation strategies to minimize the health impacts of heat waves, especially given projections of their increase across the country until 2100 (MARENGO, 2014; NOBRE et al., 2019).

Bitencourt et al. (2016) observed a trend of increasing heat waves in Brazil from 1961 to 2014, attributed to climate change and urbanization. Furthermore, there was an observed increase in mortality risk as heat waves intensified (GUO et al., 2017). Consequently, Brazil can be considered a vulnerable country in this regard.

According to Araújo (2017), extraordinary expenses for hospitalizations of children in the 27 Brazilian capitals amount to R$14.5 million per heat wave. The study also found that the effects vary according to the socioeconomic status of the hospitalized children, with 75% living in relatively poor households.

A positive correlation between heat and mortality was identified in São Paulo, with higher risks for already vulnerable population segments: the elderly, women, and individuals with lower educational levels (SON et al., 2016).

Therefore, it is crucial to promote increasingly effective management mechanisms with guidelines that account for climate change and its resultant extreme events, especially in developing countries like Brazil, with a focus on women, youth, local, and socially vulnerable communities (UN, 2022a).

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6 SOCIOECONOMIC AND ENVIRONMENTAL EFFECTS OF HEAT WAVES

Although the effects most frequently discussed in the literature concerning heat waves are related to public health, other impacts should also be considered (BITENCOURT et al., 2016). For example, Maulbetsch (2010) mentions the deterioration of potable water quality and an increase in insect populations, which can adversely affect agriculture. The proliferation of insects presents another problem. Unlike mammals, insects do not regulate their body temperature and are thus highly dependent on ambient temperatures and other climate-related environmental factors (FLUGS, 2003). Elevated temperatures and humidity enhance the living conditions for these organisms, potentially compromising crop yields and increasing the use of agricultural pesticides.

A study conducted in Rio Grande do Sul on grapevines used for producing "Chardonnay," "Merlot," and "Cabernet Sauvignon" wines found that the dormancy mechanism in grapevine buds is negatively impacted by heat waves, potentially compromising grape yields (ANZANELLO, 2022).

Moreover, prolonged periods of extreme temperatures are highly detrimental to livestock, with the impact being potentially more severe in tropical countries like Brazil (MARENGO, 2007). Vale et al. (2010) concluded that mortality rates for broilers intended for consumption are higher during periods of extreme temperatures. Additionally, Nääs et al. (2010) indicate that increased losses in beef production can reduce the competitiveness of this sector, which is significantly relevant to the Brazilian economy, accounting for 6% of the national GDP.

BITENCOURT et al. (2016) highlight that heat waves also significantly increase the demand for electrical energy due to artificial cooling systems. In this regard, the Brazilian Association of Electric Energy Distributors (ABRADEE, 2019) reports that the 2019 heat wave led to four successive records in energy demand in the National Interconnected System (SIN) within the first two weeks of the year alone. According to the Association, these figures "primarily reflect the increase in the use of air conditioning for cooling residential homes and shopping centers, as well as in street commerce and industry" (ABRADEE, 2019).

Heat waves can affect medications and may necessitate dosage adjustments under such conditions, particularly for psychotropic or antihypertensive drugs, as they can exhibit significantly different effects at extreme temperatures (TRIPPEL, 2021). Furthermore, Trippel (2021) notes that the German medical community has not been adequately prepared to manage medication dosage adjustments during heat waves, highlighting the need for the development and dissemination of technical training and scientific events on this topic. Extreme temperatures can also adversely affect the preservation of food and medications, as many require protection from heat.

Heat waves can also cause structural deformations in infrastructure not designed to withstand such conditions. In London, for example, many railway tracks experienced significant thermal expansion, warping during the summer of 2022. The responsible company, Network Rail Limited (NRL), issued a statement explaining that some tracks were designed to withstand temperatures around 27 °C (NETWORK RAIL, 2022). Painting tracks white has been adopted in

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countries such as Italy, Switzerland, and Austria, as the white color reflects a significant portion of solar radiation, helping to cool these structures. NRL also implemented this measure as an emergency response to the 2022 heat wave (NETWORK RAIL, 2022).

Jones (2022) notes that road systems can also be affected by heat waves, as occurred in England during the summer of 2022. According to the author, the heat weakened the asphalt, causing vehicle weight to create potholes and deformations in the road. Consequently, the A14 highway was closed. The British press also reported that, due to this heat wave in 2022, flights were suspended at Luton Airport after part of one runway became deformed (JACOB & FARHAT, 2022).

Ruas et al. (2020) highlight that heat waves also impact productivity and increase the risk of occupational accidents, particularly for workers in outdoor settings. A study conducted with sugarcane cutters in São Paulo State showed a correlation between worker deaths and thermal stress, which can be exacerbated by heat waves (BITENCOURT, 2012).

Recognizing these effects, public and private institutions worldwide are increasingly adopting protective measures for participants in their international events. For instance, the Tokyo Marathon and Race Walk were relocated to Sapporo by the International Olympic Committee (IOC) in 2021, considering the impacts of extreme temperatures on athletes and the public (WU; GRAW; MATZARAKIS, 2020).

7 FINAL CONSIDERATIONS

The Intergovernmental Panel on Climate Change (IPCC), a scientific-political organization within the United Nations framework, has determined through sophisticated climate prediction models that all regions of the planet will experience climate changes in the coming decades. Among these changes, the rise in average temperatures in many locations and the occurrence of extreme weather phenomena, such as heat waves, are of widespread concern to researchers and citizens worldwide (IPCC, 2022).

This study concludes that metrics such as the Heat Index can assist in understanding human perception within specific ranges of air temperature and relative humidity. Classifying this index into levels of health risk is crucial for the effective implementation of mitigating measures in response to heat waves.

It is also concluded that concerns about the harmful effects of heat waves are well-founded, as they directly impact human health, contributing to morbidity and mortality, particularly among the elderly and individuals with respiratory and cardiovascular conditions.

Additionally, it has been observed that increased frequency and intensity of heat waves may cause environmental disturbances in ecosystems and geochemical and hydrological cycles.

Abrupt changes in transportation systems and production losses in the agricultural sector also represent significant socioeconomic impacts of these climatic phenomena. In this context, it is recommended that studies be developed to examine the occurrence and intensity of future heat waves under various climate projection scenarios.

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