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Papers

The Heat Index (HI) in the city of Fortaleza, Ceará – Brazil

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Abstract
Over time, changes in space have resulted in changes in natural characteristics. In this context, thermal comfort indicators have emerged, as developed to interpret environmental conditions in relation to thermal stress. The objective of this study was to apply the Heat Index (HI) in different neighborhoods of the city of Fortaleza, which choice was based on the different types of land cover. We carried out data collection campaign at ten points in the city, using thermohygrometer sensors. We applied the HI equation to the data collected, according to the intervals of the National Weather Service and the intervals adapted for the municipality. The data indicate that Fortaleza experienced high temperatures throughout the analyzed period (dry and hot months), having a negative impact on the HI (up to 42°C). The comparison of the comfort indicator classes showed that, in the original interval, few records indicated comfortable conditions in the different neighborhoods, while the interval of classes considering the acclimatization of the population indicated situations that were more comfortable. The worst comfort conditions occurred in the afternoon, between 12 p.m. and 2 p.m. The most critical points are associated with the density of buildings and the lack of urban green infrastructure, with neighborhoods Parque do Cocó and Bairro de Fátima (with more trees) that presented the highest frequency in the comfort class. We concluded that the entire territory of the city faces thermal stress; however, green structures have the potential to mitigate the adverse effects of the thermal field, improving human comfort in the urban environment.

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INTRODUCTION

The spatial transformations that have occurred over time, especially intensified since the Industrial Revolution, have changed the way humans interact with the environment and respond to the effects caused by these changes, especially in urban environments. Santos (1993) understands that the city can be understood as a primarily human spatial organization, which modifies natural attributes in order to fulfill the demands generated by daily life. Among the natural elements that humans have been modified, especially in urban environments, it is possible to highlight the climate, where local atmospheric conditions have changed considerably over time, causing a significant increase in air temperature, anomalies in relative humidity and wind speed, and changes in local atmospheric circulation patterns (Landsberg, 1956; 1981; Chandler, 1965; Oke, 1973; Monteiro, 1976). These are resulted from the process of disorderly urban development without an appropriate planning (Gartland, 2010).

The replacement of naturally permeable soil covers, by impermeable surfaces that absorb heat and alter the energy balance of cities, aggravates the risks associated with temperature extremes (Nice *et al.*, 2022), increasing the number of heat wave episodes and their intensities worldwide (Perkins-Kirkpatrick; Lewis, 2020). It is observed that exposure to rising temperatures occurs unevenly across the city, where socioeconomic conditions and the urban environment were significant determinants of heat stress (Arifwidodoa; Chandrasiri, 2020), where the greatest exposure is linked to dense housing typologies and little vegetation in low-income informal settlements (Adegun; Ayoola, 2022).

These conditions can have a direct effect on the population's quality of life. Huang *et al.* (2011) indicate that high temperatures and excessive humidity levels can have negative effects on human health and work performance, especially when they exceed physiological limits. If the core temperature of the human body exceeds 37°C for extended periods, hyperthermia may occur (Sherwood; Huber, 2010), from temporary heat imbalances that result in heat storage in the body (Cramer; Jay, 2016).

Before causing comorbidities associated with hyperthermia, the organism suffers damage to its optimal functioning due to the sensation of thermal discomfort. To ascertain such damage, it is necessary to understand the state of the human mind and its satisfaction in relation to the thermal field (Fanger, 1970); therefore, it is necessary to use methods to evaluate the response of organisms to this phenomenon.

Thermal comfort indicators emerge in this sense, developed with the purpose of simplifying the delimitation of environmental conditions in relation to imminent stress (Blazejczyk *et al.* 2012). De Freiras and Grigorieva (2015), in a literature review study, identified a total of 165 methods or indexes to measure and evaluate thermal comfort conditions, using different inputs and levels of sophistication. The selection between different types of indexes is directly influenced by environmental conditions, the nature of the activities performed by the individual and the weighting of the relevance of each specific aspect of comfort (Annunciação, 2016), also considering the availability of *input data* for the application of the index. In the Brazilian semiarid region, for example, it was identified the application of 20 different indexes, drawing attention to the weaknesses in their applications (Paiva-Gomes; Zanella, 2023).

In the scientific literature, the Heat Index (HI) stands out among the indicators used to measure and analyze thermal comfort in hot environments. The HI combines values of temperature and relative humidity, determining the value of thermal sensation felt by individuals (Steadman, 1979), based on several biological and meteorological studies (Fanger, 1970). The HI can be applied in different regions of the globe and for different objectives, from comfort simulations according to global warming (Delworth *et al.*, 1999), analysis of heat wave cases (Suparta; Yatim, 2017; Awasthi *et al.*, 2021) and development of alert systems (Kirtsaeng; Kirtsaeng, 2015). In Brazil, studies applying HI in different areas have also been verified, mainly for microclimatic analyses (Nóbrega; Lemos, 2011; Novais *et al.*, 2021; Moreira *et al.*, 2023).

Local climate analysis is essential for understanding thermal comfort in outdoor environments, especially urban ones. The diversity of changes imposed on the landscape over short distances in cities is notorious, with different sides of the urban fabric having quite different natural and urban conditions. Would such diversity be enough to induce different thermal comfort conditions? Based on the HI, this study aimed to analyze the thermal comfort conditions in the municipality of Fortaleza, capital of the state of Ceará (Brazil), considering the different urban forms and land use conditions. It was analyzed a critical period in relation to thermal conditions in this region, represented by the month of October 2019.

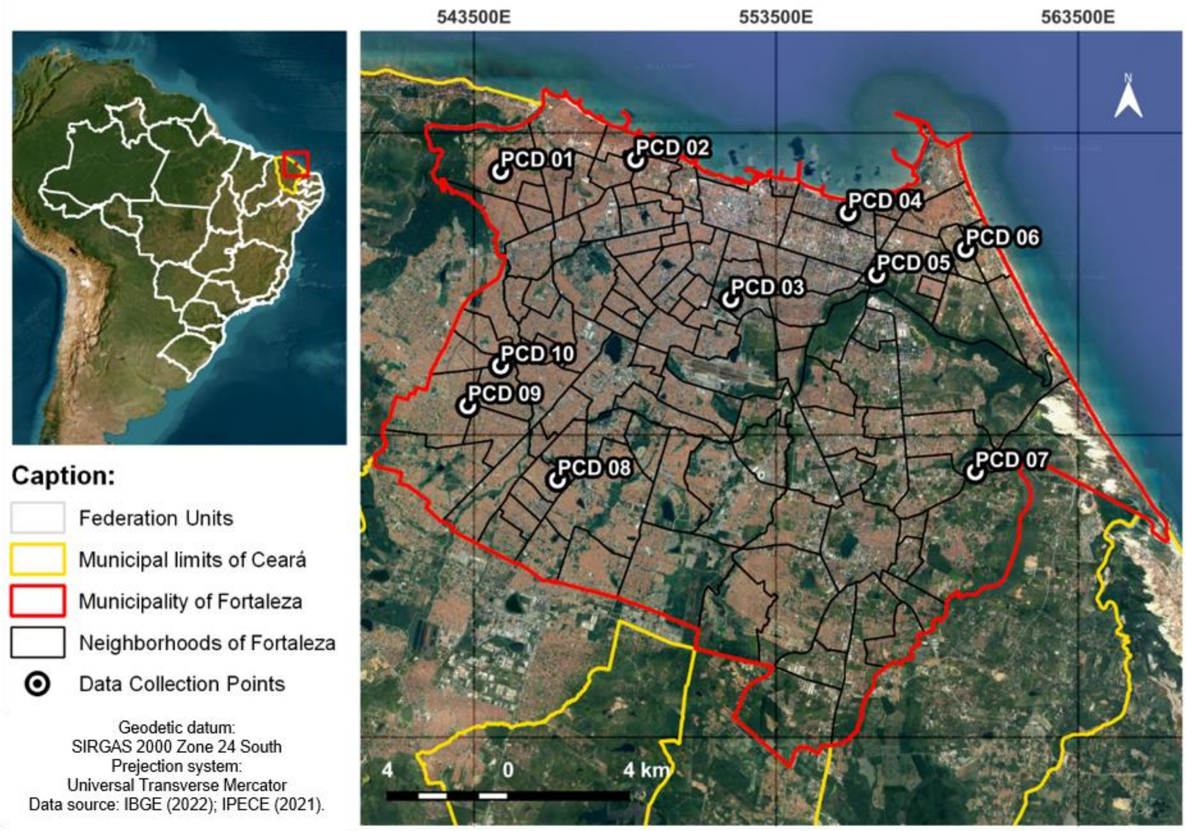
METHODOLOGY

Study area

The research was carried out using the city of Fortaleza, the capital of the state of Ceará, as its locus. This city is located at the central coordinates SIRGAS 2000 UTM Zone 24 South, 9581533.31 S and 552409.32 W (Figure 1). According to Mendonça and Danni-Oliveira (2007), Fortaleza is inserted in the context of the Tropical Equatorial Climate. Because it is located on the coast of the Brazilian Northeast region and bathed by the Atlantic Ocean, the city presents conditions of high relative humidity and great influence of the winds, on different scales.

In general, the temperature of the municipality does not suffer great intra- and inter-annual variations, where the temperature variations between the hottest and coldest months do not exceed 2°C (Moura, 2008; Lima Júnior, 2023), with the months of October, November and December reaching the highest average maximum temperatures. Therefore, what governs the climate variability in the municipality is rainfall, largely influenced by the Intertropical Convergence Zone (ITCZ), which, in turn, has its action influenced by the El Niño-Southern Oscillation (ENSO) Events and the Sea Surface Temperature (SST) in the Atlantic Ocean basin (Ferreira; Mello, 2005). In addition to the ITCZ, the main atmospheric systems that act in the production of rain in the city of Fortaleza are the Upper Level Cyclonic Vortices (VCAN), the Mesoscale Convective Complexes (CCM), the Easterly Waves (OL), among others, causing precipitation concentrated mainly in the first half of the year (Ferreira; Mello, 2005; Barbieri, 2014). In the second half of the year, situations of atmospheric stability predominate under the influence of the Atlantic Equatorial Mass (mEa).

Figure 1- Location of the municipality of Fortaleza and Data Collection Points (PCD).



Source: The authors (2024).

Currently, Fortaleza is considered one of the most important capitals in the country. According to data from the Instituto Brasileiro de Geografia e Estatística (IBGE - public institute of the Brazilian federal administration, with responsibilities related to geosciences, social, demographic, and economic statistics) (IBGE, 2023), the capital of Ceará ranks 11th among the cities with the highest GDPs in the country. According to the preliminary demographic census (IBGE, 2023), Fortaleza has 2,428,678 inhabitants, making it the fourth most populated municipality in the country. With a population density of 7,775.43 inhabitants per square kilometer (inhabit/km²), it is the eighth densest city and ranks first in this regard among Brazilian capitals.

Therefore, the municipality consists of an important urban agglomeration, without the presence of important rural areas and with a high rate of landscape modification, where only the legally protected areas maintain preserved natural characteristics, with the replacement of soil cover materials in practically the entire municipality.

Primary data collection

This article analyzed the temperature and relative humidity conditions in Fortaleza, considering different neighborhoods, which have different land use and occupation conditions and urban structure. To this end, it was necessary to carry out a primary data collection campaign using thermohygrometer sensors located at strategic points in the city. The distribution of the sensors (Figure 1) was based on the different land use patterns and geographic location, aiming to obtain a cohesive representation of the territory of Fortaleza. Chart1 presents the characteristics of each Data Collection Point.

We used HOBO MX2301A thermo hygrometers. These devices are designed to measure the temperature and relative humidity of the air (Balany *et al.*, 2022; Ma *et al.*, 2023). To use such instruments in outdoor environments, the use of a shelter is essential. These shelters, intended for thermo hygrometers, constitute protective devices, protecting the measuring instruments against the direct incidence of solar radiation and the action of the wind. Made from white PVC tubes, they have holes in the upper and lower parts, allowing air circulation and minimizing the impact of direct solar heating on the sensor. In addition, they perform the function of protecting the sensor against inclement weather, such as rain and intense winds.

Chart 1- Description of the characteristics of the research Data Collection Points (PCDs).

Aerial image	Point Description
	**PCD 01 (Alvaro Weyne)** **Coordinates:** 5448850E and 9589610S **Characteristics:** residential occupation, semi-detached residences, buildings are mostly made of masonry and the roof is composed of ceramic coverings. High density of buildings. Little afforestation.
	**PCD 02 (Vila Velha)** **Coordinates:** 544377E and 9589218S **Characteristics:** residential occupation, buildings are mostly made of masonry and the roof is made of ceramic tiles. High density of buildings. The roads are paved with asphalt and, except the main avenues, are mostly narrow. Little afforestation.
	**PCD 03 (Bairro de Fatima)** **Coordinates:** 551997E and 9584984S **Features:** mixed occupancy, larger lot size and distance between buildings. Varied template, intermediate verticalization. Paved and wide avenues. Presence of open spaces.
	**PCD 04 (Meireles)** **Coordinates:** 555887E and 9587848S **Characteristics:** mixed occupation. The paving of streets and avenues is predominantly (almost 100%) composed of asphalt material, while the most commonly used construction material in buildings is concrete, with steel structures and ceramic coatings. Consolidated verticalization and low tree cover.
	**PCD 05 (Parque do Cocó)** **Coordinates:** 556830E and 9585795S **Features:** State conservation unit. Large vegetation cover. Mixed occupation with surroundings consisting of buildings over 10 stories high. Parque do Cocó offers dedicated areas for leisure, sports, culture and environmental education activities.
	**PCD 06 (De Lourdes)** **Coordinates:** 559775E and 9586637S **Features:** high-standard residential occupation, larger lots with setbacks, in compliance with urban planning guidelines. Masonry constructions and ceramic roofs. Low volume of buildings and unbuilt lots. Close to the beach.
	**PCD 07 (Lagoa Redonda)** **Coordinates:** 559775E and 9586637S **Characteristics:** residential occupation, masonry constructions and ceramic roofs. Considerably high afforestation. Low density of buildings, considered an expansion zone. Paved and unpaved roads.
	**PCD 08 (Mondubim)** **Coordinates:** 559775E and 9586637S **Characteristics:** residential occupation, masonry constructions and ceramic roofs. High building density and few trees. Roads with asphalt paving.
	**PCD 09 (Bom Jardim)** **Coordinates:** 543292E and 9581464S **Characteristics:** residential occupation, masonry constructions and low-rise ceramic roofs. High building density and few trees. Close to the urban water supply network. Roads with asphalt paving.
	**PCD 10 (Conjunto Ceará)** **Coordinates:** 544376E and 9582784S **Characteristics:** residential occupation, masonry constructions and low-rise ceramic roofs. High building density and few trees. Close to the urban water supply network. Roads with asphalt paving.

Source: The authors (2024).

The data collection period was October 2019. The month of October was chosen due to the characteristics of strong atmospheric stability, considering that in stable atmospheric conditions, microclimatic differences are intensified (Santamouris *et al.*, 2007). This month is also among the hottest throughout the year. We recorded temperature and relative humidity data from October 1st to 31st, 2019, measuring the elements at 5-minute intervals.

Calculation of Heat Index (HI)

The Heat Index (HI) is calculated through statistical regression analyses that consider temperature and relative humidity. This method was developed based on the initial formulation of the Steadman Apparent Temperature Index, dated 1979. According to Kusch *et al.* (2004), the HI characterizes human perception when faced with various combinations of high temperature and air humidity. This occurs due to the increasing difficulty in losing heat through evaporation as humidity increases. The authors indicate the importance of the index for warning procedures, given the impacts on public health and safety.

In this work, the HI was calculated from Excel spreadsheets, where the formula was inserted, aiming to optimize the process and execute it on a large scale. The equation used to calculate the HI is described below. After calculating the HI in degrees Fahrenheit (°F), the results were converted to degrees Celsius (°C).

$$HI = 16{,}923 + [(1{,}85212 * 10^{-1}) * t_a] + (5{,}37941 * UR) - [(1{,}00254 * 10^{-1}) * t_a * UR] + [(9{,}41695 * 10^{-3}) * t_a^2] + [(7{,}28898 * 10^{-3}) * UR^2] + [(3{,}45372 * 10^{-4}) * t_a^2 * UR] - [(8{,}1497 * 10^{4}) * t_a * UR^2] + [(1{,}02102 * 10^{-5}) * t_a^2 * UR^2] - [(3{,}8646 * 10^{-5}) * t_a^3] + [(2{,}91583 * 10^{-5}) * UR^3] + [(1{,}42721 * 10^{-6}) * t_a^3 * UR] + [(1{,}97483 * 10^{7}) * t_a * UR^3] - [(2{,}18429 * 10^{-8}) * t_a^3 * UR^2] + [(8{,}43296 * 10^{-10}) * t_a^2 * UR^3] - [(4{,}81975 * 10^{-11}) * t_a^3 * UR^3] \quad (1)$$

Where:

HI is the Heat Index
UR is the relative humidity (%)
t_a is the dry bulb temperature of the air (°F)

According to information provided by the National Weather Service of the United States (NWS), Heat Index (HI) readings can be interpreted based on alert levels and potential implications for human health (Chart2).

Chart 2- HI alert levels and their possible health consequences

Alert level	Heat Index (HI)	Symptoms
Extreme danger	≥ 54 ° C	Heat stroke; risk of imminent CVA (Cerebral Vascular Accident).
Danger	41.1°C – < 54°C	Cramps, heat stroke, physical exhaustion. Possibility of brain damage (CVA) for prolonged exposure to physical activities
Extreme care	32.1°C – 41°C	Heat stroke, heat cramps or heat exhaustion possible with prolonged exposure and/or physical activity.
Careful	27.1°C – 32°C	Possible fatigue with prolonged exposure and/or physical activity.
Safe	≤ 27 ° C	No problem

Source: Adapted from National Weather Service (n.d.).

Petalas (2015) verified in her doctoral thesis the applicability of some thermal comfort indices for Fortaleza, defining new comfort limits for a series of indices that could be applied in bioclimatic analyses of open spaces in this city and in others with similar climatic and acclimatization conditions. The author presented to the HI a new range of comfort bands taking into account the acclimatization of the population of Fortaleza Chart 3).

Chart 3- HI comfort range

Comfort range	Heat Index (HI)
Uncomfortable	> 32.1°C
Comfortable	29.3°C – 32.1°C
Not designated by the author	< 29.3°C

Source: Adapted from Petalas (2015).

In this work, at the comparison level, we analyzed the data taking into account the two intervals according to the original and adapted classes of the index. The application of the HI was carried out on all the data collected, as well as for the hourly average values, finding patterns related to the thermal comfort of the city in the analyzed period.

The HI values were spatialized using the GIS software QGIS 3.28.10, using the IDW (Inverse Distance Weighted) interpolation method. This method consists of a simple estimate weighted by the distance of the value at the target station. This method produces accurate results (Musashi *et al.*, 2018), especially for regions with low topographic complexity of the terrain (You *et al.*, 2008), such as Fortaleza.

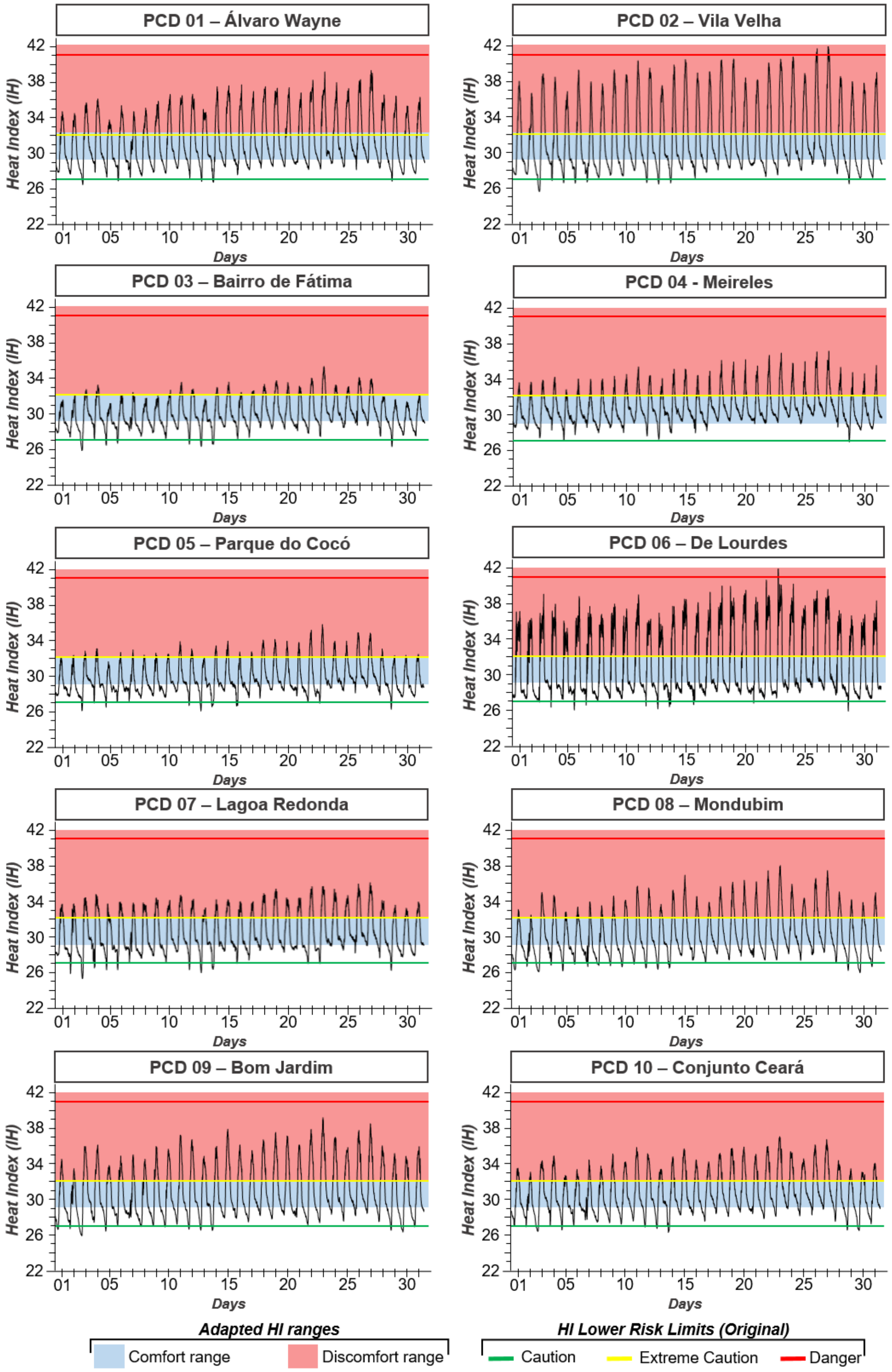
RESULTS AND DISCUSSION

The graph in Figure 2 indicates the temporal distribution of HI for each data collection point (PCD) in October 2019. This period is characterized by high temperatures and absence of rainfall, due to the direct influence of the Atlantic Equatorial Mass. The figure also indicates the range of classes of the indicator, considering the original classification and the ranges adapted by Petalas (2015), taking into account the acclimatization of the residents of the municipality of Fortaleza.

It is clear that, according to the original classes (NWS), all points present HI above comfort levels, considering the threshold of 27°C, where two points (PCD 02 and PCD 06) registered values above the danger threshold. These points represent distinct characteristics of urban land occupation, where PCD 02 is characterized by a high horizontal density of buildings, fully built-up lots and little vegetation, heating up more in the afternoon. PCD 06 is located in a dune area, with larger lots and high-end residences, where the non-built-up areas are covered by herbaceous and low vegetation, which in the dry season gives way to exposed soil, causing high and rapid heating of the surface, increasing the temperature and HI in the morning period (up to 11 am).

The graph also reveals the wide range of HI values, where the curve follows the direct solar radiation hitting the Earth's surface. At the end of the month, it is possible to see the occurrence of a heat wave, where there is a significant increase in HI at all analyzed points.

Figure 2- Variation and evolution of the HI of PCDs during the month of October 2019.



Source: The authors (2024).

Heat waves are irregular but frequent meteorological events that have a global impact, manifesting themselves through prolonged periods of high and intense temperatures over several days (Marto, 2005). In the month analyzed, between the 22nd and 27th, the occurrence of stronger temperature intensities was observed, with the period that recorded HI above the danger threshold, in Vila Velha and De Lourdes neighborhoods (PCD 02 and PCD 06).

Even during the heat wave period, PCD 03 and PCD 05 maintained the indicator values far from the danger threshold. The difference between these neighborhoods lies in the characteristics of land use and occupation assigned. PCD 03, located in the Bairro de Fátima neighborhood, has open wooded spaces, varying lot sizes, wider access roads, and intermediate verticalization with residential use. These characteristics promote greater mitigation of thermal conditions (Lima Júnior, 2023), which reflects on the result of the HI applied to local data.

According to Lima Júnior (2023), the thermal amplitude in the city of Fortaleza can reach an average of 4°C, where Parque do Cocó neighborhood is characterized as the coolest point in the urban environment. This characteristic is also reflected in the HI result for the park area (PCD 05), since it recorded the lowest associated values, including during the heat wave episode.

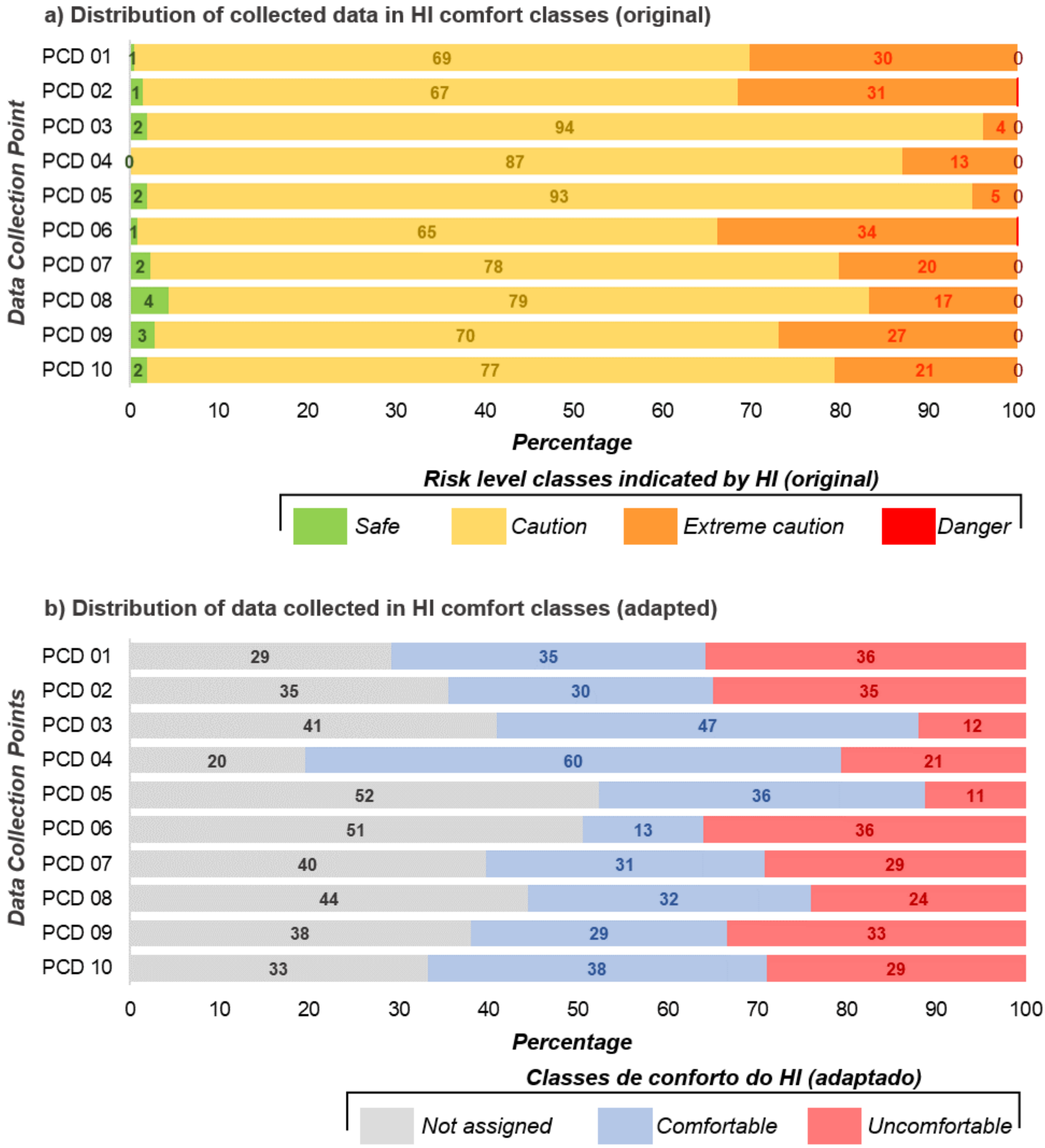
By analyzing the distribution of data in the different comfort classes (Figure 3), it is possible to identify the influence of acclimatization on the interpretation of HI, taking into account the classes indicated by the NWS and by Petalas (2015).

In the original classification (NWS), the point that presented the highest percentage of data within the safe comfort class was PCD 08, located in the Mondubim neighborhood (4%), while PCD 04 (Meireles) did not register temperatures within the established comfort range. Considering that, in Fortaleza, the comfort condition is always verified at night during the analyzed period, this absence of HI conditions considered comfortable in Meireles neighborhood exposes a situation of less nocturnal cooling of the materials. This is perfectly plausible in an area where concrete is the most common construction material, while in several other neighborhoods of the city, such as the aforementioned Mondubim, masonry is the predominant material.

The points Álvaro Weyne, Vila Velha and Lourdes (PCD 01, PCD 02 and PCD 06, respectively) recorded the highest percentages of data classified in the extreme care class (30%, 31% and 34%, respectively). This highlights that at the Vila Velha and De Lourdes points (PCD 02 and PCD 03) measurements were found above the danger level.

Taking into account the acclimatization of the population of Fortaleza, Petalas (2015) established a new range for the comfort and discomfort thresholds based on the HI result, considering that individuals who remain for prolonged periods of time in hot climates have a greater capacity to tolerate high temperatures compared to those from colder regions (Andreasi, 2009). Therefore, the upper HI comfort threshold, that is, the onset of discomfort, which was 27°C, became 32.1°C.

Figure 3- Distribution of collected data in HI comfort classes.



Source: The authors (2024).

When evaluating the distribution of the collected data, taking into account the population's acclimatization, the percentages that fall within the comfort threshold increase. The points located in the neighborhoods Bairro de Fátima and Parque do Cocó (PCD 03 and PCD 05, respectively) were those that obtained the highest percentage of data considered non-uncomfortable (88%). It is possible to see a difference between the NWS classification, both in the percentage value and in the representative points.

The points that recorded the lowest percentages considered non-uncomfortable were those located in Álvaro Weyne, De Lourdes and Vila Velha neighborhoods (PCD 01, PCD 02 and PCD 06) with 64%, 64% and 65%, respectively. Despite the discrepancy in the percentages verified in both HI class intervals, the same neighborhoods were the most problematic in relation to the situation of thermal discomfort.

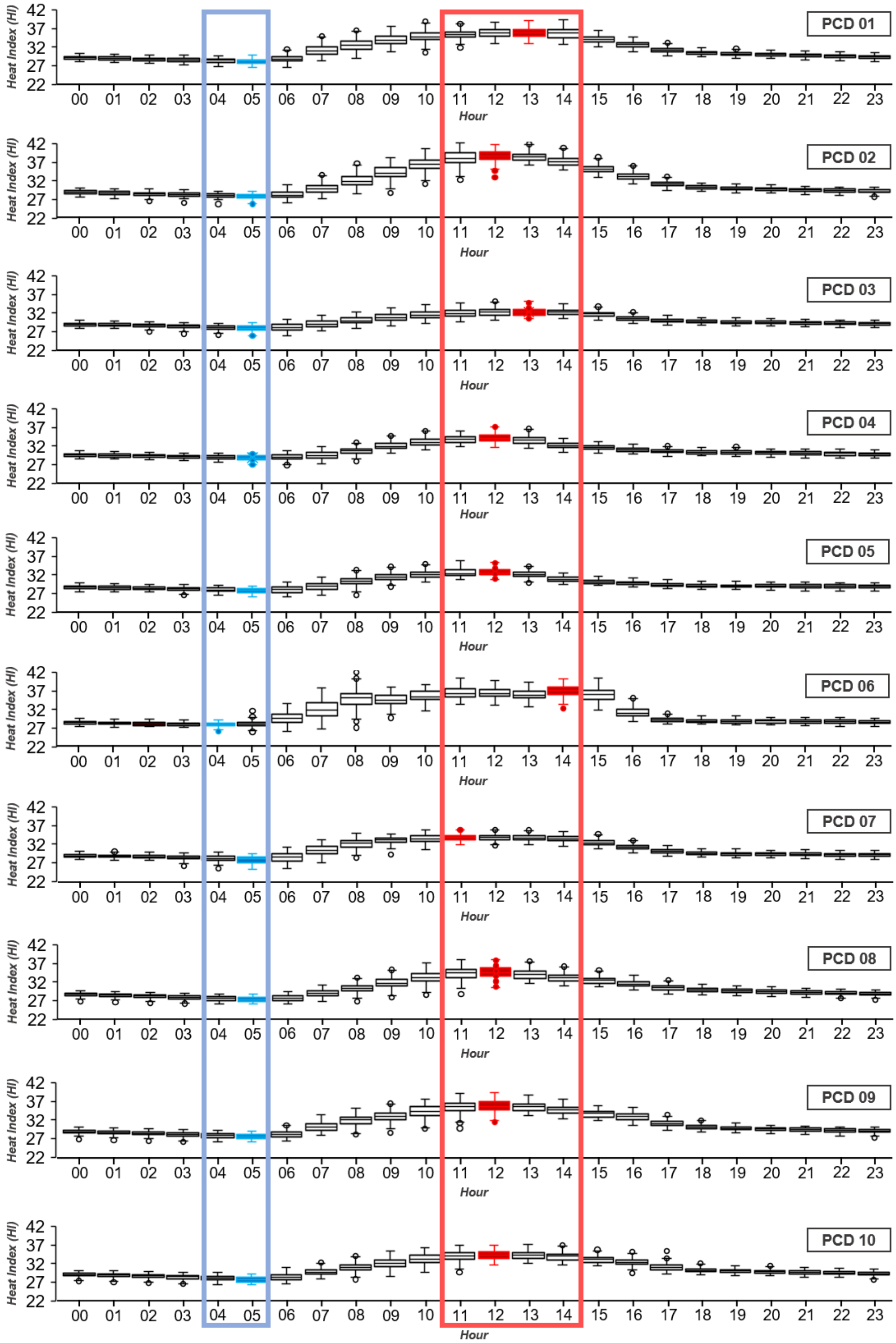
It is necessary to unravel the data into hourly scales, since the behavior of the city's thermal conditions is directly related to the incidence of solar radiation and the physical environment of the city. Studies of urban climate in Fortaleza, from the perspective of the thermal field (Moura, 2008; Moura; Zanella; Sales, 2008; Lima Júnior, 2018; Lima Júnior, 2023) indicate that the most intense manifestations of the urban heat island in the city occurred during the daytime (between 7 am and 3 pm). The analysis of the result of the hourly averages of the HI is in line with what the literature for the municipality reported.

The analysis of the hourly distribution of the HI result during the month of October 2019 helps to understand the thermal comfort in the city of Fortaleza (Figure 4). As with the amplitude of the heat island, the intensity of the HI result is more pronounced during the daytime period, where from 7 am there is a significant variation in the collected values, persisting in this pattern until 4 pm.

In this time slot, due to direct insolation from solar radiation, higher temperature values are recorded. Another important factor to be considered in the analysis is the predominant synoptic condition of Atlantic Equatorial Mass (mEa), which causes climate stability and, therefore, a greater accentuation of the influence of local conditions on the thermal field (Santamouris *et al*., 2007).

The highest hourly HI values were recorded from 11 am to 2 pm, the period of direct incidence of solar radiation on the Earth's surface. The lowest records occurred between 4 am and 5 am, in agreement with local scientific literature, which indicates that these times have the lowest air temperature records and the lowest intensity of the urban heat island.

Figure 4- Box plot of the hourly distribution of HI for the month of October 2019.



Source: The authors (2024).

The Data Collection Points (PCDs) that recorded the highest and lowest HI values in each hourly period were analyzed (Figure 5), with the aim of understanding how the dynamics of land use and coverage interfere with the city's thermal comfort behavior.

Figure 5- Identification of the points with the highest and lowest value records for each hourly average of the HI.

	00h - 02h	03h - 05h	06h - 08h	09h - 11h	12h - 14h	15h - 17h	18h - 20h	21h - 23h
PCD 01	28.95	28.34	30.83	34.75	35.75	32.63	30.20	29.59
PCD 02	28.72	28.04	30.09	**36.20**	**38.11**	**33.25**	29.98	29.37
PCD 03	28.80	28.11	29.09	**31.47**	32.24	30.75	29.57	29.27
PCD 04	**29.45**	**29.00**	29.71	33.01	33.33	31.05	**30.27**	**29.94**
PCD 05	28.54	28.02	29.07	32.12	**31.90**	**29.78**	29.04	28.93
PCD 06	**28.31**	28.02	**32.19**	35.57	36.46	32.17	**28.83**	**28.71**
PCD 07	28.77	28.08	30.25	33.39	33.69	31.25	29.42	29.20
PCD 08	28.36	**27.57**	**29.00**	33.05	33.94	31.44	29.63	29.03
PCD 09	28.55	27.80	30.08	34.23	35.30	32.51	29.81	29.20
PCD 10	28.82	28.06	29.73	33.09	34.13	32.15	30.03	29.49

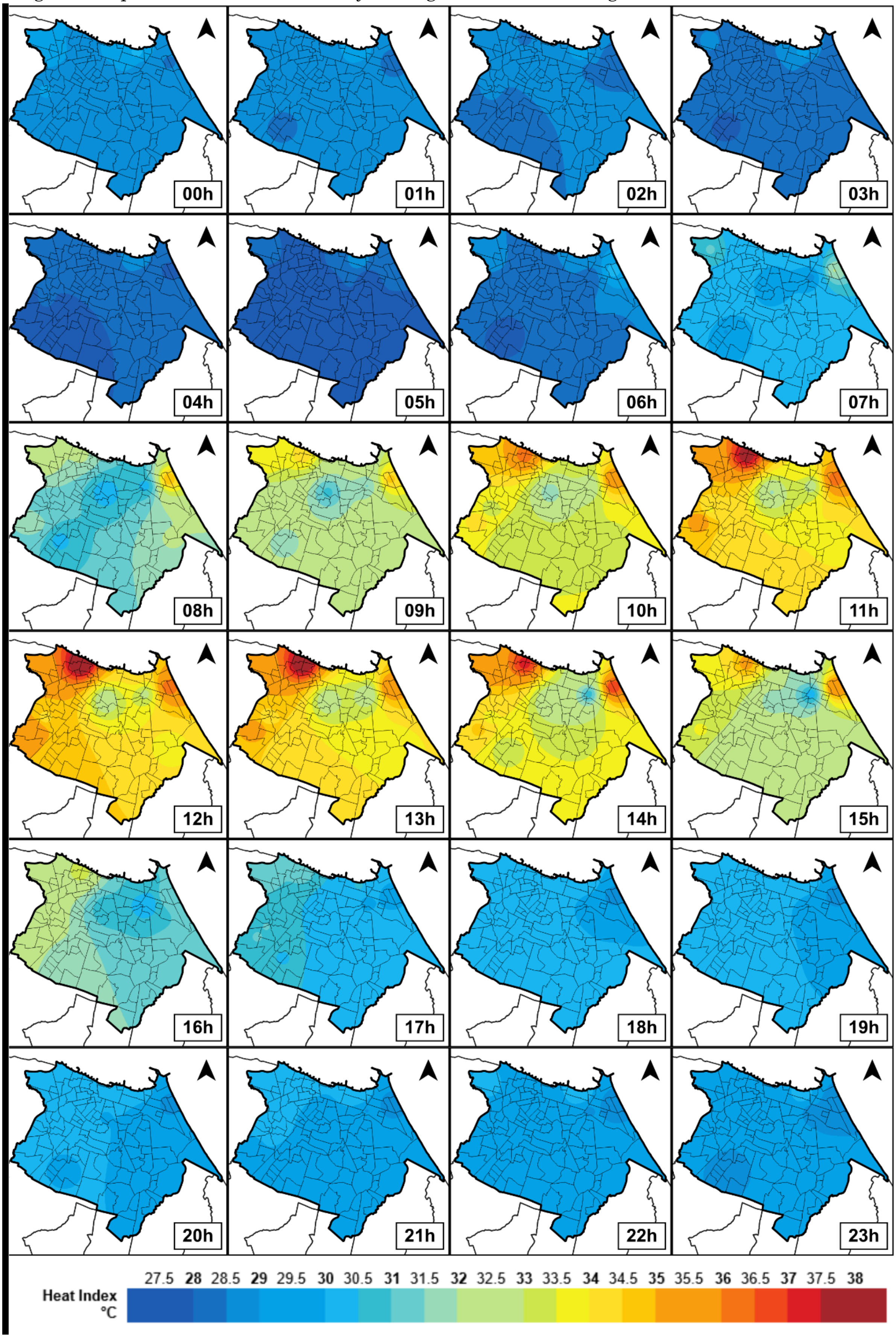
The variation in shades of blue represents the lowest values and the variation in shades of red represents the highest values recorded for that time.
Source: The authors (2024).

The points located in Álvaro Weyne, Vila Velha, De Lourdes and Bom Jardim neighborhoods (PCD 01, 02, 06 and 09, respectively), were those that recorded the highest hourly averages during the daytime period (between 6 am and 5 pm). The Meireles neighborhood (PCD 04) was the one that recorded the highest HI records during the night and early morning, due to the already mentioned difference in construction materials and the consolidated verticalization process observed in the neighborhood. During the day, the shading of the buildings provides a positive effect on thermal conditions, since it protects the surface from the incidence of direct solar radiation. However, the processes of multiple reflectances and prolonged heat storage produced during the day cause the higher air temperature during these periods.

During the period of greatest sunlight, between 9 am and 5 pm, the points located in Bairro de Fátima and Parque do Cocó neighborhoods show milder conditions in terms of air temperature and, consequently, HI as well. There is almost a difference of more than 6°C between the coolest point (Cocó) and the hottest point (Vila Velha), during the afternoon (between 12 pm and 2 pm). This difference is directly associated with the characteristics of land use and occupation in these neighborhoods.

The hourly averages of the HI were spatialized (Figure 6) indicating the areas of the city with thermal comfort and discomfort conditions in the Fortaleza territory.

Figure 6- Spatialization of the hourly averages of the HI during the month of October 2019.



Source: The authors (2024).

For better visualization of time differences, we assigned the same temperature classes, with an interval of 0.5°C.

It is clear from the analysis of the cartograms that the outskirts of the city of Fortaleza suffer from the intensity of thermal discomfort, with the northwest, west and southwest sectors presenting and maintaining the highest HI values during the day. These areas have a high population density and, consequently, a high density of buildings, contributing to unfavorable thermal conditions.

This same region is also where a larger percentage of the population with lower purchasing power and more vulnerable to climate variations lives, which can lead to reflections associated with socio-environmental inequality and climate injustice, as in the work of Paiva (2014).

Another sector that presented unfavorable HI conditions was the northeast sector of the city, around De Lourdes neighborhood, however, with less intensity in the afternoon and greater intensity during the early morning, due to the aforementioned natural characteristics of the surroundings of PCD 06.

FINAL CONSIDERATIONS

The city of Fortaleza is located in a region with a high incidence of solar radiation, contributing to high temperatures throughout the year. The heterogeneous characteristics of use and occupation of the urban surface of the municipality contribute to significant differences in the manifestation of air temperature, contributing to the disparity in the thermal sensation of city dwellers.

The city does not have an efficient system for monitoring thermo-hygrometric variables, with few fixed points for measuring these variables in its territory, and for work such as the one described here, it is necessary to install temporary measuring points. Investment in solutions (increasing the monitoring and modeling network) is necessary for an understanding of the thermal field in its real conditions and manifestations.

With the sensors installed and accurate data collected, it was possible to understand the city's thermal comfort in the context of a hot and dry period. The Heat Index (HI), at the NWS thresholds, indicates a situation of discomfort in all the evaluated neighborhoods, while, in the classification that takes into account the acclimatization of the inhabitants, the comfort conditions were significantly higher.

Even at the most critical times on days when a heat wave episode occurred, areas with more green infrastructures can alleviate thermal discomfort conditions at a local level. In this context, Parque do Cocó neighborhood is an important urban instrument for thermal comfort in the city of Fortaleza, showing the lowest HI values at times already defined by the literature as having the highest intensity of Heat Island.

This research presented a framework of information about the city's thermal field during a critical period. It is important to highlight the need to include analyses for other periods of the year and locations in the municipality, taking into account more types of atmospheric weather and more land use conditions.

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