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Thermal comfort indices applied to the city São João de Pirabas, Northeast Pará

Índices de conforto térmico aplicado à cidade de São João de Pirabas, Nordeste Paraense

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Abstract: The large concentration of people in urban areas in a tropical region (hot and humid) is one of the recurring problems when it comes to thermal comfort. The objective of this study was to analyze the thermal comfort in the municipality of São João de Pirabas-PA. Meteorological data (air temperature and relative humidity) were collected using 3 microloggers, HOBO U10 model, programmed to record every 30 minutes, from 8 am to 6 pm. The equipment were installed inside suitable shelters in order to protect it from external interference. Data collection took place from June 20th to 22nd, 2023, simultaneously in pre-defined locations, taking into consideration the surface coverage. In this research, the following were used: Heat Index (HI), Effective Temperature Index (ETI) and Thermal Discomfort Index (TDI). The daily air temperature averages of the three previously exposed locations were around 30.4°C; 28.1°C and 30.2°C, while relative humidity varied between 69%; 83% and 70%. The CI presented little temporal variation, the ETI and TDI showed differences between the point 1 (discomfort) compared to the others. The city needs measures to improve thermal comfort.

Keywords: Meteorological variables; Heat; Pará Coast.

Resumo: A grande concentração de pessoas em zonas urbanas em uma região tropical (quente e úmida) é uma das problemáticas recorrentes quando se trata de conforto térmico. O objetivo deste estudo foi analisar o conforto térmico do município de São João de Pirabas-PA. Os dados meteorológicos (temperatura do ar e umidade relativa do ar) foram coletados usando 3 microloggers modelo HOBO U10, programados para realizar os registros a cada 30 minutos, no período das 08 às 18 horas. Foram instalados no interior de abrigos adequados, a fim de protegê-los de interferências externas. A coleta dos dados ocorreu nos dias 20 a 22 de junho de 2023, de forma simultânea em locais pré-definidos, levando em consideração a cobertura da superfície. Nesta pesquisa foram utilizados os: Índice de Calor (IC), Índice de Temperatura Efetiva (ITE) e o Índice de Desconforto Térmico (IDT). Nas médias diárias da temperatura do ar, dos três locais expostos anteriormente, ficaram em torno 30,4 °C; 28,1 °C; 30,2 °C, enquanto a umidade relativa variou entre 69%; 83%; 70%. O IC apontou pouca variação temporal, o ITE e IDT mostraram diferenças entre o ponto 1 (desconforto) comparado aos demais. A cidade precisa de medidas para melhorar o conforto térmico.

Palavras-chave: Variáveis meteorológicas; Calor; Litoral Paraense.

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1. Introduction

Currently, around 55% of the world's population lives in urban areas, and this proportion is expected to increase to 68% by the year 2050 (UN, 2018). Given this scenario, understanding and improving thermal comfort in urban areas becomes an essential objective in several scientific fields, especially meteorology, which plays a fundamental role in this area of study. As indicated in the study by Shu et al. (2022), there is clear evidence that the human body is significantly affected by temperature and humidity, as these elements are intrinsically linked to the exchange of heat and humidity between the body and the external environment. In this context, land use and coverage play a crucial role in thermal comfort, directly and indirectly influencing weather and climate conditions (Fernandes; Masiero, 2020; Shu et al., 2022). These factors also have an impact on other aspects, such as agriculture and urbanization (Rahimi; Nobar, 2023). In Brazil, an increase in cases of heat waves has been observed in the last five decades, especially in the northeast and southeast regions, as well as in the Amazon and Pantanal biomes (Libonati et al., 2022). Studies conducted by Bitencourt et al. (2016; 2020) have highlighted this trend, while evidence shows that heat waves are increasingly associated with periods of drought in these regions. Therefore, it is necessary to seek measures to understand this problem and take assertive measures to mitigate the impacts of thermal discomfort.

On-site assessment is of great importance due to its ability to provide real environmental conditions observations. Furthermore, assessment through indices plays a crucial role in providing characterization and parameters related to environmental conditions (Santos Júnior et al., 2016). Field studies, such as developed by Krüger et al. (2018), who evaluated comfort and discomfort environmental conditions, using the Physiological Equivalent Temperature (PET) index, combined with applied questionnaires, are of great relevance to this topic. The use of the Thermal Discomfort Index (TDI) created by Thom (1959) involves analyzing the impact of meteorological variables, such as air temperature and relative humidity, on human thermal comfort. This index classifies different categories of discomfort, allowing people to determine their level of discomfort. Furthermore, the adaptive comfort theory, mentioned by Din et al. (2014), can be applied to evaluate thermal comfort in different environments. The TDI is widely evaluated in several studies, such as Dasari et al. (2021) and Santos et al. (2023). In several studies, multiple indices are used for the purpose of comparing and obtaining a comprehensive view of environmental conditions. The joint assessment of the Effective Temperature Index (ETI) and the Heat Index (HI), as carried out by Moreira et al. (2023) when applying these two indices in the Eastern Amazon, it can be considered a promising approach. These indices, as reported by Silva Júnior et al. (2012a) and Costa et al. (2013), can be considered robust indicators to evaluate thermal exchanges in the Amazon region.

Studies on thermal comfort in the Amazon and especially in the state of Pará (Barbosa et al. 2015) have been carried out to evaluate thermal comfort, using metrics such as HI. Among these studies, the research carried out by Silva Junior et al. (2012b), who investigated thermal comfort conditions *in situ* in the city of Belém, the capital of Pará, using the HI as an evaluation parameter. Furthermore, Silva Junior et al. (2012a) also conducted an *on-site study* evaluating environmental conditions using ETI and HI. However, there are few studies associated with IDI in the state of Pará, especially *on-site approaches*. It is worth highlighting the study by Mandú et al. (2021), who evaluated the TDI on an annual basis in a location west of Pará. From this perspective, it is crucial to carry out studies on environmental thermal comfort conditions in several locations in Pará, including specific areas in the northeast of the state. Therefore, the objective of this study was to investigate the practical application of thermal comfort equations and indexes, highlighting the importance of *on-site studies* to understand environmental conditions more precisely. By providing an in-depth analysis of thermal comfort conditions in a municipality in the northeast of Pará, São João de Pirabas, this study seeks to contribute to the development of strategies and interventions that promote healthier environments that are adaptable to the needs of the population.

2. Methodology

The municipality of São João de Pirabas is located in a tropical region in the Northeast portion of Pará (Figure 1) and plays an important role in fish extraction, having a territorial extension of 668.4 km ^{2}, with around 20,647 people (Brito et al., 2015; IBGE, 2019).

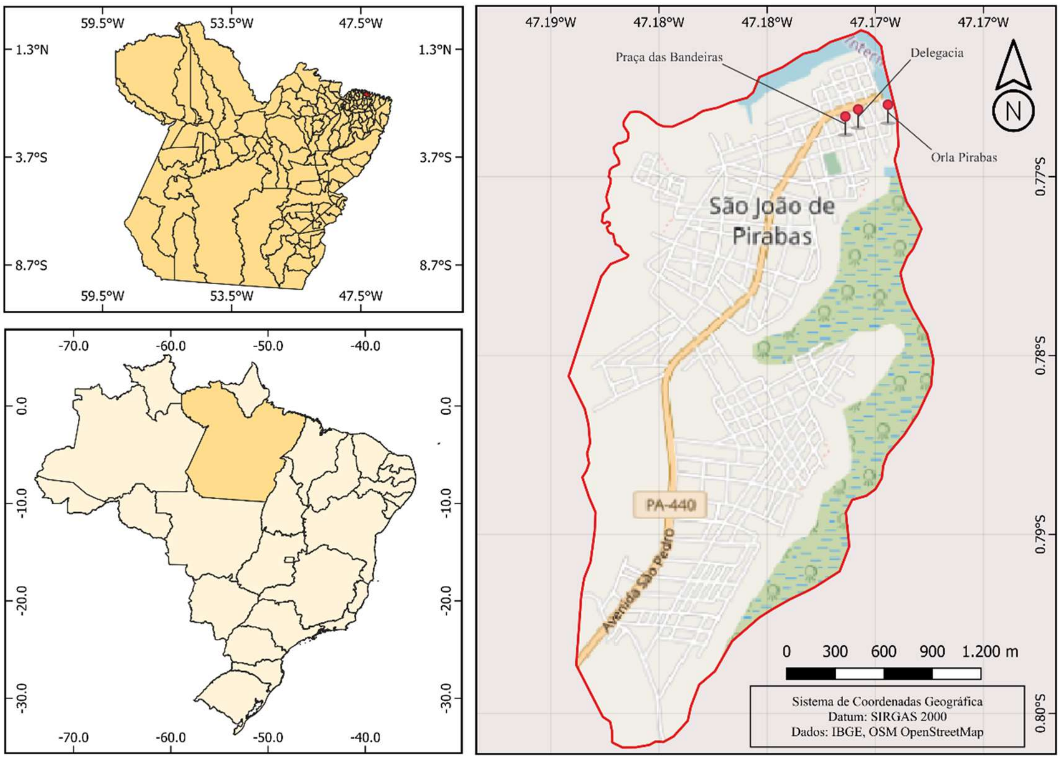

Figure 1 – Location of the study area and data collection points: São João de Pirabas.
Source: Authors (2023).

2.1 Climatology

The climate of the city of São João de Pirabas is characterized as hot and humid, where the precipitation regime is well defined, with high volumes of precipitation marking the rainy period between December and May (summer solstice and autumn equinox), as well as as the least rainy period in which there is a reduction in precipitation between June and November (Figure 2). It is worth highlighting the action of meteorological phenomenon that cause precipitation, which affect the sector studied: the Intertropical Convergence Zone (ITCZ), the High Level Cyclonic Vortex (HLCV) and the Eastern Wave Disturbance (EWD); these systems are characterized as synoptic that determine precipitation and local temperature (Reboita et al., 2010; Reboita et al., 2017; Neves; Alcântara; Souza, 2016; Teodoro; Reboita; Escobar, 2019; Lyra; Arraut, 2020 ; Liu et al., 2022).

Furthermore, as the study site is located in a coastal region, there are systems associated with local effects that contribute to the rainfall regime, such as Instability Lines (IL) and the Circular Mesoscale Convective System (CMCS) classified as mesoscale phenomenon (Sodré et al., 2015; Sátyro, 2021).

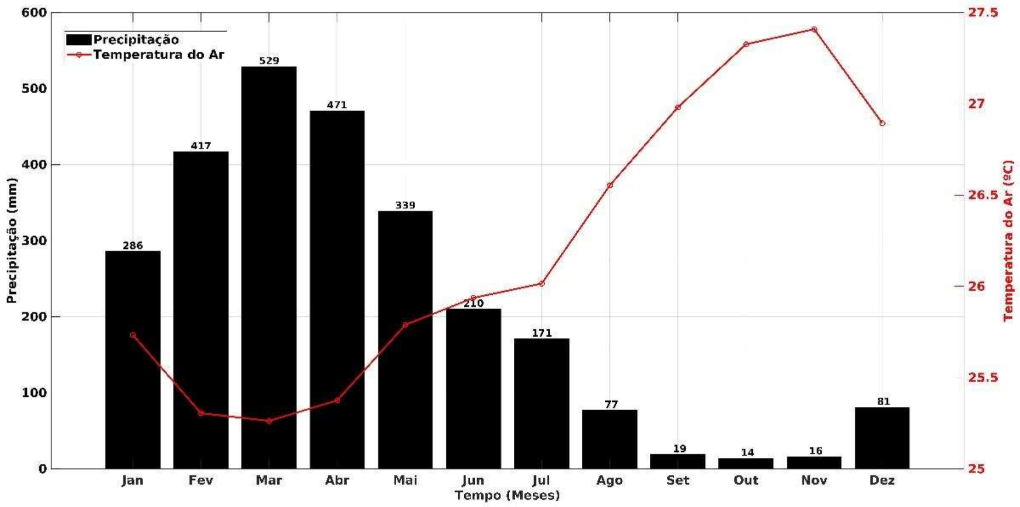

Figure 2 – Monthly rainfall (1981-2020) and air temperature (1991-2020) variability: municipality of São João de Pirabas (PA).
Source: Adapted from CHIRPS (2023).

2.2 Dados

The meteorological data were collected using 03 microloggers, HOBO U10 model, from Onset, which are devices whose purpose is to measure and record the temperature and relative humidity of the air, as well as being programmed to carry out the recordings every 30 minutes, during the period from 08 to 18 hours. Installed inside suitable shelters, in order to protect it from the direct incidence of solar radiation and enabling appropriate ventilation.

The locations of the data collection points are shown in Figure 3. Data collection took place from June 20th to 22th, 2023, simultaneously in pre-defined locations in the city center and surrounding areas, from 8am to 6pm, taking into account the characteristics of surface use and coverage (Santos Júnior et al., 2016).

The collection points have spatially distinct characteristics, mainly in the geographic component (Figure 3). The first location, the waterfront, is concentrated further east of the city and presents a more open area, with winds coming from the ocean, with the presence of green areas and an asphalted and cemented surface. Then, the second collection site was the São João de Pirabas Police Station, located in the most urbanized area and with the presence of physical barriers that interfere with air circulation more directly, in addition to having a large concentration of asphalted area; and finally, the third point was in the most central region of the city, Flags Square (Praça das Bandeiras), where the rate of green areas is higher than other locations, but there is moderate circulation of vehicles and people during the day.

Figure 3 – Data collection points in São João de Pirabas, highlighting the geographical layouts of the locations: Point 1 - Waterfront (a), Point 2 - Police Station (b) and Point 3 - Flags Square (c).
Source: Authors (2023).

2.3 Thermal Comfort Indexes

Thermal comfort indexces emerged in the 20th century, during the Industrial Revolution, where there was a need for improvements in performance and work efficiency. Therefore, were developed some indexes in order to determine the effect of meteorological variables such as air temperature and humidity on the workers physical performance (Silva Júnior et al., 2013).

According to Batiz et al. (2009), thermal comfort is related to man's intuitive search for wellness, in addition to being directly linked to the cognitive process linked to physical, physiological, psychological processes, etc. In this research, three indexes were used to evaluate and compare their applicability to the region, these being: Heat Index (HI), Effective Temperature Index (ETI) and Thermal Discomfort Index (TDI). The HI is a branch of the *humidex index* developed in 1978 by George Winterling and adapted by Steadman in 1979. The HI associates values of temperature and relative humidity to determine the apparent temperature, in order to represent the body's thermal sensation (NOAA, 2023).

To carry out the calculation, the Steadman methodology (1979) was applied, whose index is a function of the maximum temperature and relative humidity of the air, according to Equation 1:

$$HI = -42{,}379 + 2{,}04901523 * T + 10{,}14333127 * RH - 0{,}22475541 * T * RH - 0{,}00683783 * T^2 - 0{,}05481717 * RH^2 + 0{,}00122874 * T^2 * RH + 0{,}0085282 * T * RH^2 - 0{,}00000199 * T^2 * RH^2 \quad \text{Eq. 1}$$

Where:
HI – Heat Index (°C)
T – Maximum air temperature (°C)
RH – Relative air humidity (%)

Therefore, the results generated through the calculation are shown in Table 1, together with the thresholds and consequences associated with the values obtained.

Table 1 – Alert thresholds based on the Heat Index (IC) and their consequences for the human body.

Classification	**Heat Index**	**Effects on the Body**
Absence of alert	HI < 27°C	---
Careful	27.1°C – 32°C	Fatigue possible with prolonged exposure and/or physical activity
Extreme Care	32.1°C – 41°C	Heatstroke, heat cramps, or heat exhaustion are possible with prolonged exposure and/or physical activity
Danger	41.1°C – 54°C	Heat cramps or heat exhaustion are likely, and heatstroke is possible with prolonged exposure and/or physical activity
Extreme Danger	> 54°C	Heatstroke highly likely.

Source: Authors (2023).

For the ETI, Thom's (1959) methodology was used, as shown in Equation 2:

$$ETI = 0,4 * (T_{air} + T_w) + 4,8 \qquad \text{Eq. 2}$$

Where:
ETI – Effective Temperature Index (°C)
T_{air} – Air temperature (°C)
T_w - Wet Bulb Temperature (°C)

The ETI (Table 2) is an index widely used to characterize the effects of temperature and humidity on thermal comfort (Silva Júnior et al., 2012a). Furthermore, it has excellent applicability in places where climatological data is scarce (Buriol et al., 2014).

Table 2 – Comfort thresholds based on the Effective Temperature Index (ITE).

Effective Temperature Index	**Comfort thresholds**
35.0°C – 40.0°C	Very uncomfortable
28.0°C – 34.9°C	Uncomfortable
26.0°C – 27.9°C	Slightly uncomfortable
23.0°C – 25.9°C	Comfortable
20.0°C – 22.9°C	Slightly comfortable

Source: Adapted from Silva Júnior (2012).

In relation to the TDI, it also uses the relationship between temperature and relative humidity applied in Equation 3:

$$TDI = T_{air} - (0,55 - 0,0055 * RH) * (T_{air} - 14,5) \qquad \text{Eq. 3}$$

Where:
TDI – Thermal Discomfort Index
T_{air} – Air temperature (°C)
RH – Relative Air Humidity (%)

The TDI was initially developed by Thorn (1959) whose thresholds were suitable for the tropical region, as shown in Table 3.

Table 3 – Classifications based on the Thermal Discomfort Index (TDI).

Thermal Discomfort Index	Thermal Discomfort Level
TDI < 24°C	Comfortable
24°C – 26°C	Partially Comfortable
26°C – 28°C	Uncomfortable
IDT > 28°C	Very uncomfortable

Source: Adapted from Santos (2018).

3. Results and discussion

Figure 4 shows the variability of temperature (4a) and relative humidity (4b) from June 20th to 22nd, 2023, collected: Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Flags Square). The collections took place over 10 hours, from 8:00 am to 6:00 pm and it was possible to observe the performance of the variables according to the atmospheric conditions that occurred during the period.

The daily air temperature averages of the three previously exposed locations were around 30.4 °C; 28.1°C and 30.2 °C, while relative humidity varied between 69%; 83% and 70%. The minimums recorded in both variables occurred at the beginning of the day , when the readings began , and the maximums around 12 noon and 2 pm. It is worth mentioning that the variability observed between these three locations occurred in very different ways, due to geographic configurations, such as spatial arrangements and configurations of land use and coverage.

The prevailing meteorological conditions during this period corroborated to the patterns observed throughout the series, especially during the last two days of observations. It is possible to notice that during the beginning and the end of the afternoon of 07/21, there was a drastic reduction in the observed temperature values and a sharp increase in relative humidity, due to the approach of a precipitating meteorological system in the study area, associated with the differential heating of the surface and mesoscale phenomenon, such as IL, leading to intense short-term precipitation, with an accumulated rainfall of 48 mm.

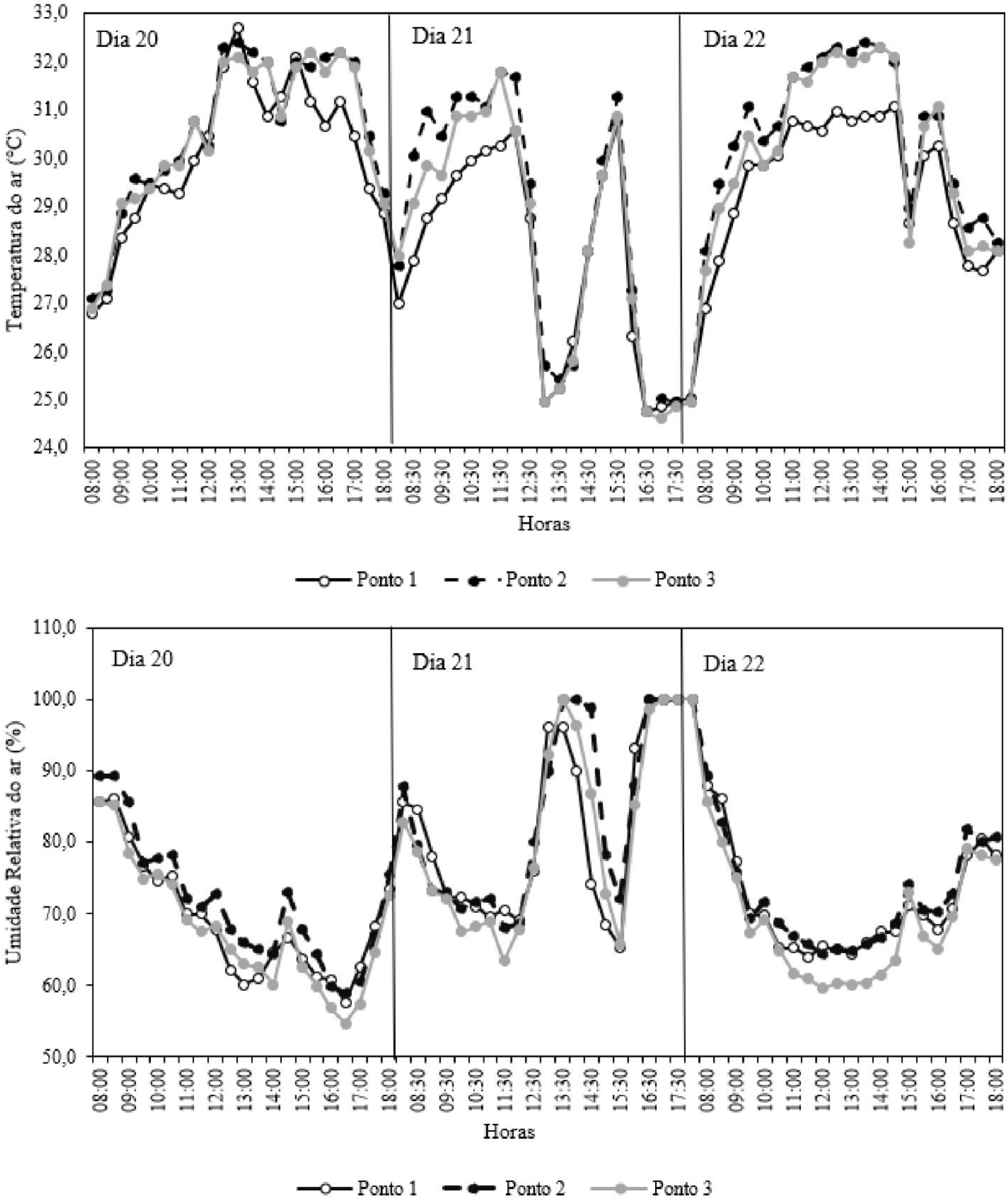

*Figure 4 – Temperature variability (a) and relative humidity (b), during the 20th, 21st and 22nd of June 2023, in three different locations in the city of São João de Pirabas. * Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Flags Square).*
Source: Authors (2023).

3.1 Thermal comfort índices

In Figure 5, the variation in HI can be seen during from 20th to 22nd of June, 2023, for the three measurement points proposed for the research. A similar behavior was identified at the measurement points, obtaining little variation during the day from one location to another. It was analyzed that HI values begin to increase from 12pm onwards, as solar radiation intensifies, influencing the city's thermal comfort. For the measurement days, it is noted that most of the results are in the "very careful" range, with the HI varying between 32°C and 41°C. The days 20th and 22nd of june had the maximum peaks reaching the "danger" range. For day 21, minimum HI peaks were recorded between the analyzed period, obtaining HI ranges, such as: Attention and absence of alert.

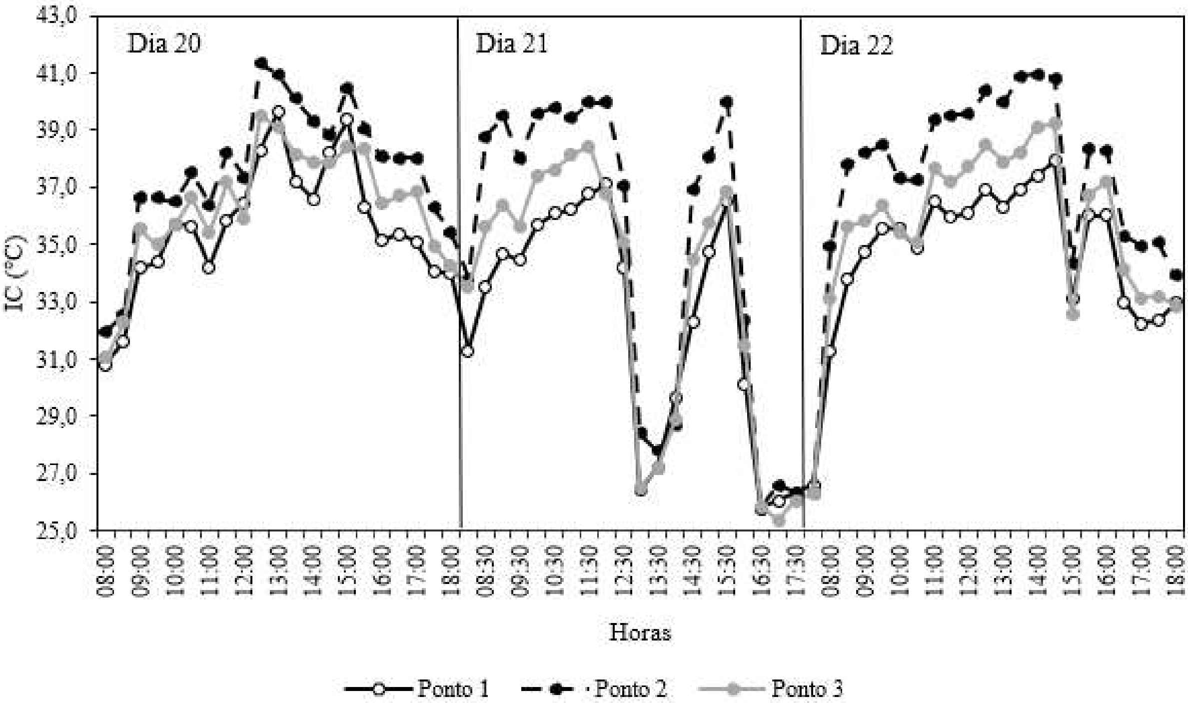

*Figure 5 – Variability of the heat index (HI), during the 20th, 21st and 22nd of June 2023, in three different locations in the city of São João de Pirabas. The colors in the graph represent: blue (lack of attention), yellow (caution), orange (extreme caution), and red (danger). * Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Square).*
Source: Authors (2023).

Figure 6 presents the ETI, the index analyzed showed that the early morning and late afternoon at points 2 and point 3 presented a comfortable threshold, especially on day 22, when most of the afternoon the ETI gradually decreased by around 3°C. At point 3, most of the daytime period, the ETI resulted in the "slightly uncomfortable" range (except at 2:00 pm on the 22nd when the threshold was comfortable). The index showed that at point 1, for the most part, it presents ranges, such as: slightly uncomfortable, and obtaining "uncomfortable" ranges, indicating an intensification of the ETI precisely at point 1, at this measurement point the ETI values vary between approximately 24, 4°C and 28°C.

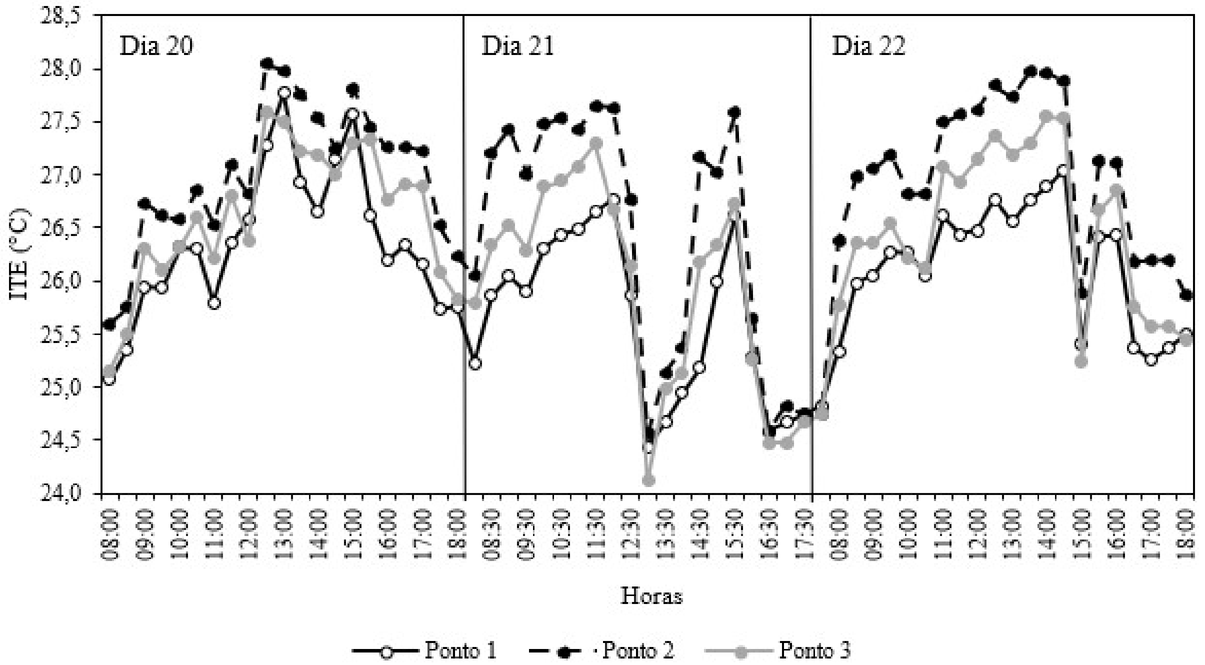

*Figure 6 – Variability of the effective temperature index (ETI), during the 20th, 21st and 22nd of June 2023, in three different locations in the city of São João de Pirabas. The colors in the graph represent: blue (comfortable), yellow (slightly uncomfortable), and orange (uncomfortable). * Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Flags Square).*
Source: Authors (2023).

In Figure 7, the TDI can be seen, at point 1 it reveals higher values of the index compared to the other locations, indicating greater thermal discomfort, the IDT values vary between approximately 24.7°C and 29.1°C throughout of the measurement period, indicating ranges of uncomfortable and very uncomfortable, observed on all measurement days of this study. At point 3, conditions indicate the uncomfortable range or higher at some intervals. TDI values vary between approximately 24.4°C and 28.6°C throughout the measurement period. At point 2, the IDT values are lower, signaling greater thermal comfort, although a large part of this result is in the discomfort range.

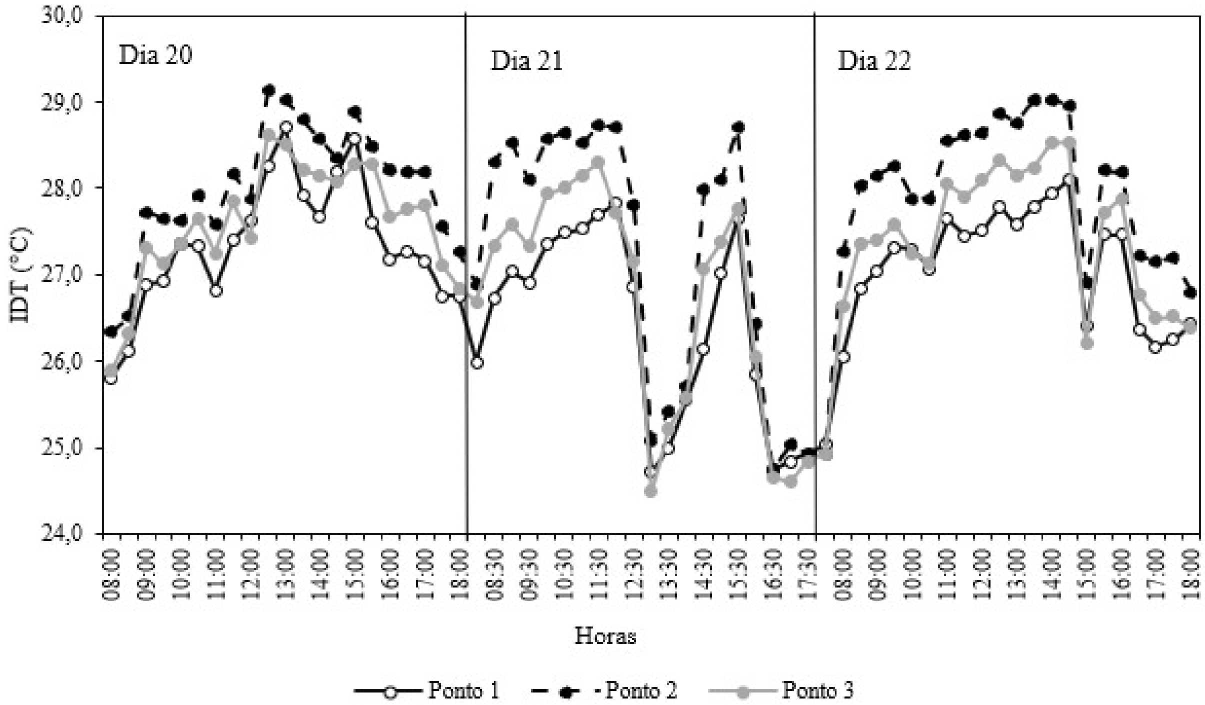

*Figure 7 – Variability of the thermal discomfort index (TDI), during the 20th, 21st and 22nd of June 2023, in three different locations in the city of São João de Pirabas. The colors in the graph represent: Yellow (partially comfortable), orange (uncomfortable), and red (very uncomfortable). * Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Flags Square).*
Source: Authors (2023).

According to the results, it is notable that the thermal comfort indices (HI, ETI, TDI) have a similar variation according to the days analyzed, even obtaining a similar oscillation. Among the points studied, the critical level according to the indices are point 1, point 2 and point 3, respectively. Around point 1, local characteristics directly influence the results obtained, these being: presence of walls and asphalt, low circulation of people and grassy area with low trees. Therefore, these local characteristics result in less heat dispersion and shading and less cooling provided by plant evapotranspiration, in addition to local buildings storing and retaining heat. This contributes to the increase in temperature and, consequently, negatively influences the result of calculating thermal comfort indices. Furthermore, it is the place where the presence of walls and asphalt is more perceived, which means low albedo, that is, it reflects lower solar radiation, further increasing the sensation of thermal discomfort, even at times when precipitation has been recorded.

Point 3 is the place where there is more trees among the other two places and with more movement of people, so that, the movement of people and vehicles results in greater dispersion of heat generated by human activities and urban mobility. This way, heat does not accumulate in the area, reducing the area temperature and positively influencing the results in the calculation of thermal comfort indices, favoring a more pleasant microclimate in relation to the police station.

At point 2, the presence of grass and trees favors cooling through the shade and evapotranspiration present, contributing to a more pleasant thermal sensation. But the main factor that made point 2 the place with one of the lowest thermal comfort thresholds was its proximity to the river, as the albedo of the water is relatively higher, which means greater reflectivity of solar radiation, reducing heating of the environment. Furthermore, the presence of water favors evaporation and the formation of sea breezes, when cooler and denser air over the ocean moves to the coast, contributing to cooling and a better thermal sensation (Germano et al., 2016). Natural refrigeration (through evaporation) and more laminar air flow in relation to the other two measurement points ventilation (local predominant winds are from the northeast) through the breeze resulting from air circulation from the temperature difference between the water and the environment around, contributing to cooling and better thermal sensation.

3.2 Correlation between variables

The air temperature and relative humidity are inversely proportional meteorological variables, that is, the higher the air temperature, the lower the relative humidity will be, since the air becomes drier and this reduces the amount of water in the atmosphere. Thus, the correlation between these meteorological variables is negative and significant, as shown in Figure 8 for points 1, 2 and 3. The relationship between these variables and thermal comfort indices basically follows the same pattern, in which, for the temperature of the air, there is a strong and positive correlation, so that when there is an increase in air temperature, the index values proportionally return to uncomfortable or very uncomfortable thresholds. For point 1 and point 2, the ETI shows a weaker negative correlation for air humidity, compared to point 3 which is closer to -1.

The correlation between the indices is significant and positive, and their values tend to vary together, suggesting that the three indices are being captured in a consistent and concordant way with the perception of thermal comfort in relation to environmental conditions.

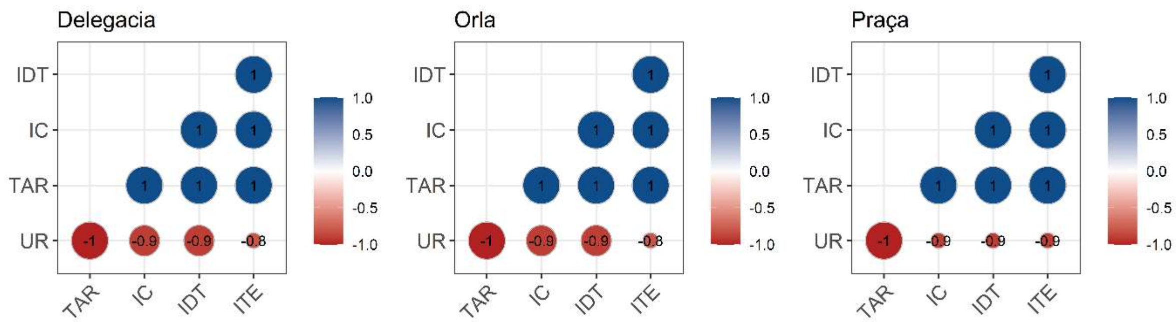

*Figure 8 – Correlation matrix between meteorological variables (TAR, RH) and thermal comfort indices (HI, ETI, TDI), during the 20th, 21st and 22nd of June 2023, in three different locations in the city of São João from Pirabas. * Point 1 (Police Station), Point 2 (Waterfront) and Point 3 (Flags Square).*
Source: Authors (2023).

4. Final considerations

Based on thermal comfort indices, it can be seen that the city of São João de Pirabas largely presented unfavorable conditions for thermal comfort, with thermal discomfort ranges being much more present during the day in the city, except during periods of rain, due to greater wind intensities and relative humidity. The heat index showed very high values, which is very harmful to human health, according to the thresholds presented in the table for this index. Furthermore, it is important to note that the study was carried out in a tropical region, during the less rainy season, which indicates greater thermal discomfort.

Given these thermal comfort indexes, it is important that the population of São João de Pirabas is aware of the challenges posed by the local climate and adopts measures such as higher afforestation measures in areas with a lack of vegetation cover, to guarantee their wellness during periods of intense heat. There are also strategies such as wearing light and breathable clothing, looking for air-conditioned or well-ventilated environments and adequate fluid intake, which are essential to minimize the effects of thermal discomfort and maintain a more satisfactory feeling of comfort.

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