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Thermal Sensation in Courtyards: Potentialities as a Passive Strategy in Tropical Climates

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Received: 4 July 2020; Accepted: 28 July 2020; Published: 30 July 2020

Abstract: Climate change will bring changes to our living conditions, particularly in urban areas. Climate-responsive design strategies through courtyards can help to moderate temperatures and reduce the thermal stress of its occupants. Thermal response inside courtyard is affected not only by its morphological composition but also by subjective factors. Thus, standardized thermal scales may not reflect the stress of the occupants. This study investigated the impact on thermal attenuation provided by a courtyard located in a tropical climate under extreme cold and hot synoptic conditions by means of local thermal sensation scales. Microclimatic variables were monitored, simultaneously with the application of a thermal comfort questionnaire, by using weather stations installed outside and inside the courtyard. The Modified Physiological Equivalent Temperature Index (mPET) was utilized to predict the heat stress. Calibration was conducted using linear regression to attribute particular thermal sensation votes to correspondent mPET values. It was found that thermal sensation can be affected by factors such as psychological, behavioral, and physiological. The courtyard's form provides a passive cooling effect, stabilizing interior thermal sensation, with attenuation peaks of 6.4 °C on a cold day and 5.0 °C on a hot day. Courtyards are an alternative passive strategy to improve thermal ambience in tropical climate, counterbalancing climate change.

Keywords: climate-responsive design; courtyard; tempering potential; thermal comfort; tropical architecture; insolation; aspect ratio

1. Introduction

A courtyard is defined as an open space surrounded by buildings which plays a role in providing natural lighting, ventilation, and shading for internal building environments. Previous research has addressed the direct relationship between humans, architecture, and the environment, emphasizing the importance of the relationship between the internal and external spaces of buildings. This relationship is fundamental to improve the quality of life for users through a more sustainable architecture [1]. Courtyards comprise a passive bioclimatic strategy, with the potential to provide a milder microclimate and mitigate the internal thermal conditions of their delimitating buildings, consequently leading to improved thermal comfort, due to the arrangement and proportion of full and empty volumes that these constructions create in the built environment [2]. Therefore, its passive potential may contribute to resilience to the urban heat island phenomenon, therefore also being beneficial for the mitigation of global warming [2,3].

Courtyards are an ancient architectural feature traditionally found in hot and dry climates, such as in the desert. However, they have also been applied to other regions, comprising Mediterranean, cold, hot, and humid climates [2–7], and have been widely used in buildings in Asian and European countries, as well as in North Africa, China, and Latin America [6]. In Brazil, this type of construction is present in several historical buildings, brought by European colonizers [8], although dwellings with courtyards are not part of the Luso-Brazilian tradition and rarely used in contemporary projects due to lack of diffusion about their advantages in the country, in particular, their passive climate control capacity.

The literature indicates the existence of research on courtyards in the most diverse climatic regions, focusing on the following characteristics: (a) physical, where courtyard shape, configuration, geometric proportions, and solar orientation are examined [2,4,6]; and, (b) environmental, focusing on their thermal performance, ability to provide natural ventilation, shading, sunshine, and thermal comfort conditions [5–7,9–11]. The impact of courtyards in some climates has been assessed both qualitatively and quantitatively, mainly using field measurements [2,9] and computational modeling [6,11], with emphasis on the hot-dry and Mediterranean regions, where these constructions act as a microclimate regulator, offering shading and sun protection, as well as influencing natural ventilation patterns. Thermal performance courtyard assessments are also relevant in high-temperature and humid climates, such as tropical climates, in which few recent investigations have been conducted regarding the influence of thermal courtyard conditions on the thermal sensation of the occupants of these open spaces [6,11].

The thermal sensation of a courtyard is influenced by air temperature and humidity, wind speed, and radiant temperature, the latter related to solar radiation incidence and shading conditions [12,13]. Courtyards are able to provide a thermal sensation stabilizing effect, due to their height and width proportions, as well as their solar orientation [6]. In addition, their morphological composition (colors, textures, and materials, among others) and natural elements (vegetation, flowers, and water, among others) also influence their microclimate and, consequently, the thermal comfort of their occupants [14]. Thus, courtyard orientation, aspect ratio (relation between height and dimensions), and its Skylight Vision Factor (SVF) are important variables that affect the shadows cast by the building and the received solar radiation, influencing thermal performance in diverse climates [6,11].

In this sense, Martinelli and Matzarakis [11] conducted a study using a computer simulation that evaluated the predicted thermal sensation using the Physiological Equivalent Temperature (PET) index, concluding that higher height and width ratios (H/W) result in a stabilizing thermal comfort effect. This effect is favorable in both the winter and summer, and most noteworthy in the latter, resulting in more benefits in courtyards located in hot climates. In a similar study, Rodríguez-Algeciras et al. [6] altered courtyard orientation and geometry, e.g., the aspect ratio, of a large courtyard (convent type) located in the historic center of Camagüey-Cuba. Aspect ratio greater than 1 is recommended, as this contribute to improved thermal courtyard conditions in the summer, reducing courtyard sub-areas where the average radiant temperature (Tmrt) is above 45 °C. In this context, Krüger, Drach, and Broede [15] evaluated the thermal perception of individuals in different urban geometry conditions and found that, under medium SVF conditions, users declared lower heat thermal sensations compared to those who remained more exposed to the open sky, with a high SVF.

It is important to note that people entering a courtyard, in addition to interacting with its morphological composition, are influenced by subjective factors, such as psychological (past experiences, expectations, and autonomy, among others), behavioral (the type of adjustment to the environment, which includes changing clothes, activity level, posture, movement in space, and searching for shaded places, among others), and cultural factors (difference in attitude toward the sun, imposition of clothes use for norm reasons, etc.), which can affect thermal perceptions [14,16]. Recent studies in courtyards usually apply standardized thermal sensation scales that do not reflect the thermal sensation of their occupants, which can lead to errors and inaccuracies regarding thermal condition acceptability [6,10,11]. Therefore, additional research efforts are required to evaluate and precisely quantify the thermal sensation in courtyards and their climate-resilient capacity, such as their potential to attenuate occupant sensation and, in this way, providing an adequate alternative to counterbalance climate change impact.

Thus, this study investigates the cooling and heating capacity provided by a courtyard located in a tropical climate and its respective impact on thermal sensation attenuation in extreme cold and hot synoptic conditions, by means of local thermal sensation scales, addressed by thermal comfort questionnaire. Linear regression is used to attribute particular thermal sensation votes to correspondent modified Physiological Equivalent Temperature Index (mPET) values. This research contributes to studies on the topic, since it presents a methodology that considers the influence of occupant adaptation and subjective factors, as well as morphological courtyard factors, on the resulting thermal perception, in addition to the need to appropriately apply thermal sensation scales. This assessment also contributes to further knowledge related to courtyards implemented in tropical climates, providing subsidies for future studies that intend to incorporate a closer relationship between architecture and the local climate, still incipient in the study region.

The paper is structured as follows. The introduction focuses on the need to consider the morphological composition and subjective factors in thermal sensation of the courtyards' occupants. The Methodology includes on-site monitoring of outside and inside microclimatic variables, application of thermal comfort questionnaires, procedures to derive local thermal sensation scales, and environmental thermal impact evaluation provided by the courtyard. Results present characterization of personal and microclimate variables, followed by thermal sensation scales derived for the courtyard occupants and the thermal impacts provided by courtyard as a passive strategy. The discussion helps to clarify the potentiality of the courtyard to act as a passive cooling and heating strategy, as well as providing attenuation on thermal sensation in tropical climates.

2. Materials and Methods

2.1. Study Area

This study was carried out in the municipality of Cuiabá (15°36′36′′ S; 56°11′04′′ W), capital of the state of Mato Grosso, in Midwestern Brazil (Figure 1). The climate is classified as a semi-humid Continental Tropical or Tropical Savanna climate (Aw, as per Köppen-Geiger classification), presenting two very distinct seasons: one rainy (hot-humid between spring and summer, from October to April) and one dry (hot between autumn and winter, from May to September) [17]. The average, minimum, and maximum annual temperatures are 27.9 °C, 23.0 °C, and 30.0 °C, respectively. The annual relative humidity average is 71.6% and precipitation, 1372.2 mm [18]. The region's climate can also be defined by three periods: a dry and cooler season in winter, a hot, dry transition season, just before the rains, and a hot, wet season, during the summer rains [19].

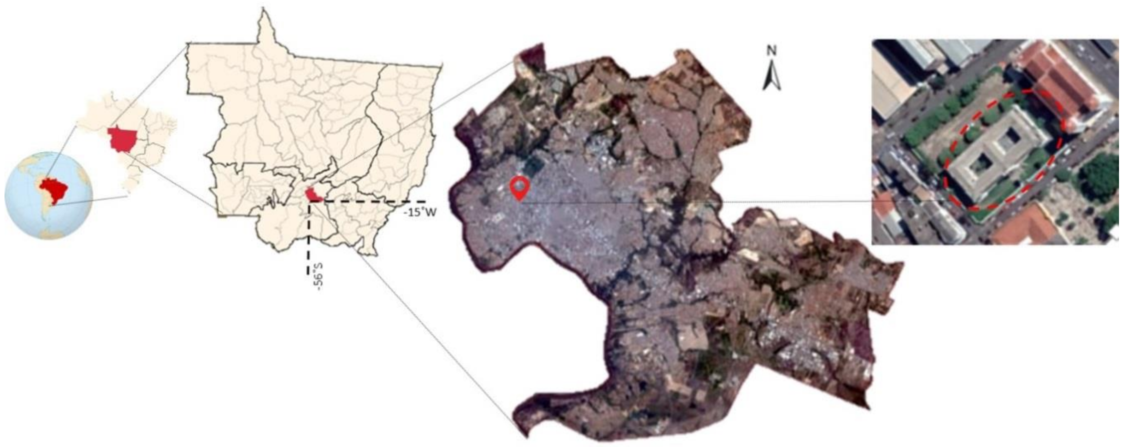
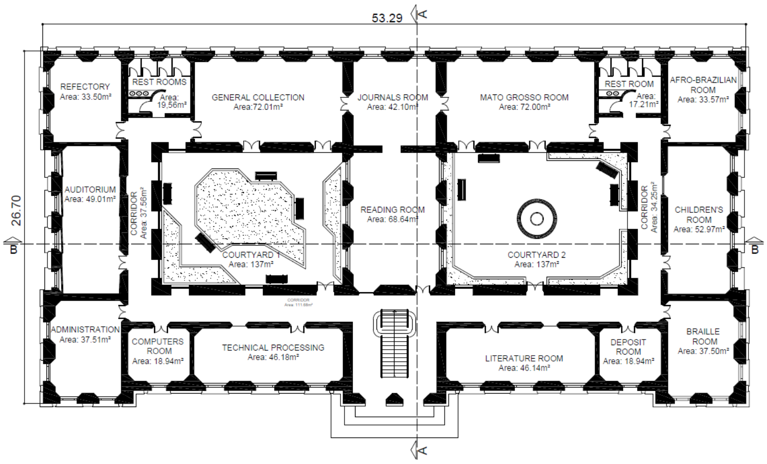


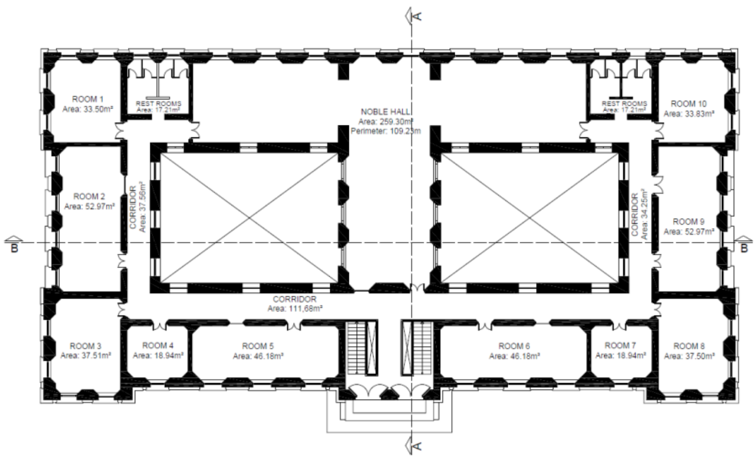
Figure 1. Location of the courtyard in the city of Cuiabá and South America.

2.2. Characterization of Courtyard

As it is an architectural element most commonly found in historic buildings, the internal courtyard of the Palácio de Instrução building, which housed a traditional "Cuiabana" school in the first half of the 20th century, was selected as the study object. Built-in historic-eclectic style (dominated by classical origin elements) in 1914, it is located in the historic center of the city, a high urban densification region, and is currently the headquarters of the local Museum of Natural History and Anthropology and the Public Library. The building has two floors and two central rectangular courtyards, 13.7 m wide (W), 10 m in length (L), and 11.8 m high (H), with the maximum aspect ratio H/W = 1.18. The building project (plan and sections) can be visualized in Figure 2 and a picture of the existing building/courtyard in Figure 3.



(**a**)



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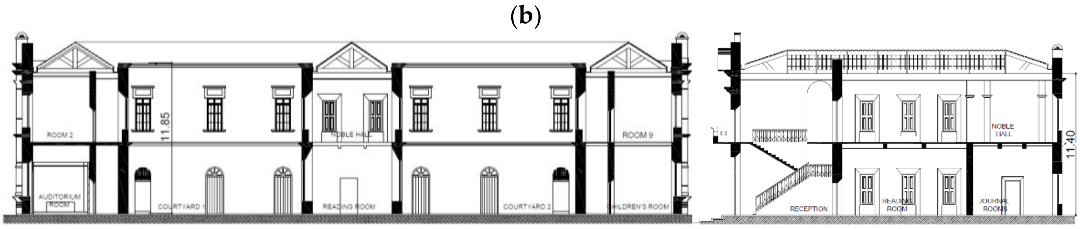
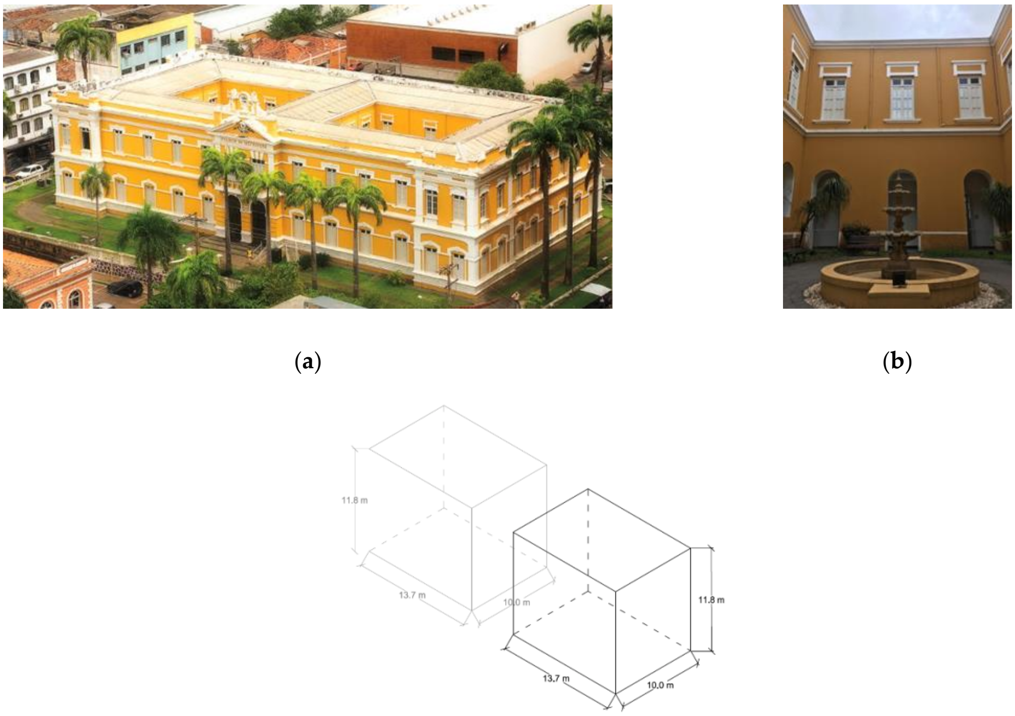


Section BB Section AA

(**c**)

Figure 2. (**a**) First floor plan, (**b**) second floor plan, and (**c**) sections of the Palácio da Instrução project (dimensions in meters, drawing without scale).



(**a**) (**b**)

(**c**)

Figure 3. (**a**) View of the Palácio da Instrução Building (Adapted from [20], p.42, photo by Téo de Miranda); (**b**) from the courtyard; (**c**) axonometry. Case study geometric diagram.

The courtyards were designed taking into reference monastery cloisters, with adjacent communication to corridors that circulate almost the entire building. In addition to offering social interaction, they are responsible for providing ventilation and lighting to corridors through windows (with low sills) and passageways. To perform measurements, the right courtyard was chosen, which has a Baroque-style fountain in the center, and in its perimeter there is a garden plant, with a presence of shrubs and grass. The building follows the general rules indicated by Rodríguez-Algeciras et al. [6] for a courtyard set in a hot and humid climate, which establishes that it must have three floors and be positioned along the NE-SO axis, to set an efficient shading performance index.

2.3. Microclimate Monitoring Equipment

Two meteorological stations (Figure 4) were used to measure the environmental variables inside and outside, in the near surroundings, aiming at obtaining a local scale of thermal sensation.

The recording of outdoor temperature data was carried out through an automatic meteorological station installed on the roof of the building (approximately 12 m), equipped with solar radiation (Rg), atmospheric pressure (pa), air temperature (Ta), relative humidity (RH), globe temperature (Tg), and air speed (Va) sensors. A datalogger was used to record inside courtyard data, with air temperature (Ta), relative humidity (RH), and globe temperature (Tg) sensors. With the exception of the globe thermometer, installed at 2.0 m, the other instruments were positioned in the courtyard at 1.1 m, corresponding to the average height of the center of gravity of adults. Records were stored as averages every 5 min. All sensors meet ISO 7726 [21] recommendations and were calibrated before the experiment.

(a)

(b)

Figure 4. Meteorological stations installed (**a**) outside the building and (**b**) inside the courtyard.

To derive the mean radiant temperature (Tmrt), the ISO 7726 [21] equation for forced convection transcribed in Equation (1) was used:

$$Tmrt = \left\{\left(T_g + 273\right)^4 + \left[\frac{\left(1.1 \times 10^8 \times {V_a}^{0.6}\right)}{\left(\varepsilon_g \; x \; D^{0.4}\right)}\right] \times \left(T_g - T_a\right)\right\}^{1/4} - 273, \quad (1)$$

where T_g represents the globe temperature, T_a the air temperature, V_a the airspeed, with ε_g and D, the emissivity (0.95), and the diameter of the globe (0.063 cm) used in the research.

2.4. Questionnaire Application to Derive the Declared Thermal Sensation

Parallel to courtyard microclimate monitoring, questionnaires were applied to courtyard users to obtain information about their declared thermal sensation. The first part of the questionnaire comprised personal data (sex, age, height, and weight) and information about their length of residence in the region (acclimatization), length of stay in the courtyard, health status, and estimated isolation by clothing, recorded through the ISO 9920 [22] procedure. Exclusion criteria consisted of time spent in the city for less than six months, time spent in the courtyard for less than five minutes, and declaration of any symptom of illness. In the second part of the questionnaire, respondents were asked about their thermal sensation vote (TSV) through the use of the symmetric intensity scale of seven points (Likert scale) proposed by the ISO 10551 standard [23] (-3, cold; -2, cool; -1, slightly cool; 0, neutral; 1, slightly warm; 2, warm; 3, hot), the vote of acceptability and tolerance of the thermal environment.

The derivation of the local thermal sensation categories adapted to the study site, according to the users' perception inside the courtyard, was obtained considering the answers to the question presented in Table 1.

Table 1. Thermal sensation scale used in the present study.

Question: "Right Now, How Are You Feeling (Choose According to the Scale Below)?						
Response Intensity Scale						
−3	−2	−1	0	+1	+2	+3
Cold	Cool	Slightly cool	Neutral (thermal neutrality)	Slightly warm	Warm	Hot

The choice of days and times of the year for the measurement campaigns took into account the scope of the three seasons observed in the study region, between July 2019 and February 2020 (hot-dry, transition, and hot-humid). The questionnaires were applied from 8 a.m. to 6 p.m. (local time), obtaining a sample of 88 answers, considered statistically adequate, taking into account the population that frequents the building's courtyard [24].

2.5. Thermal Stress-Modified Physiological Equivalent Temperature Index (mPET)

The original Physiological Equivalent Temperature index (PET) underestimates the influence of water vapor pressure in hot and humid environments and considers only a standard garment condition (0.9 clo). To correct these issues, Chen and Matzarakis [25] developed the modified physiologically equivalent temperature index (mPET), which is based on the equilibrium condition of the semi-unstable energy flow of the human body, maintaining the same condition as the internal virtual PET reference environment (Ta = 20 °C, water vapor pressure - VP = 12 hPa, v = 0.1 m/s and Tmrt = Ta).

In this research, the derivation of the thermal stress by the mPET Index was performed using the Rayman Pro software [26]. The input data consisted of the climatic variables of air temperature, relative humidity, average radiant temperature, air speed, and metabolic rate, considered as 80 W/m^2, the standard value for the standard virtual mPET environment. Data on height, weight, and age required for the calculation of the index were applied as those of the average man and the average woman, established by the ISO 8896 standard [27]. The thermal resistance of the clothing of the occupants of the courtyard was obtained by observing the clothes that the respondents wore at the time of the questionnaire application, through an ISO 9920 equivalence [22].

2.6. Calibration Procedure-Derivation of Local Thermal Sensation Categories

Studies have indicated that the morphological composition of built and natural elements is one of the main determinants of the microclimate of an outdoor environment and, consequently, of the thermal comfort feeling of its occupants. In addition, subjective factors (psychological, behavioral, and physiological) can also influence thermal perception.

In this sense, the research instruments applied herein designed to capture these influences and the local ranges of thermal sensation were derived from the responses considering votes of sensation and thermal preference, concurrently. The following criteria were considered to establish thermal perception limits: (a) thermal comfort range was defined based on responses in which users declared that they stated neither feeling cold nor feeling hot stress during the interviews (vote 0) and declared themselves to be comfortable with the thermal environment; (b) the range of discomfort due to hot and cold stress was defined based on the perception responses in which users declared themselves to be feeling a slightly warm (vote +1), warm (vote +2), or hot stress (vote +3, 0) and slightly cool (vote −1), cool (vote −2), or cold (−3) at the same time that they declared themselves to be uncomfortable or very uncomfortable with the thermal environment (Table 2).

The mean thermal sensation vote (TSV) was calculated by applying the methodology proposed by De Dear and Brager [28], at 1 °C mPET intervals, in order to estimate the mPET range based on the stated votes. At least five respondents were used for each grouped thermal sensation vote average for each 1 °C interval (mPET), to avoid biased thermal sensation votes. This procedure generated a scatter plot between mean thermal sensation vote (TSV) (y-axis) and mean mPET values (x-axis), from which a linear regression curve was fitted. This was carried out due to its simplicity and the fact that non-linear regressions curves failed to provide significantly more precise adjustments, evaluated by the coefficient of determination (R^2). The derived linear equation was used to determine the Neutral Temperature (TSV = 0) and to obtain local thermal sensation scales for the courtyard occupants, derived from the mPET values. In the case of cold TSV classes, values below −0.5 were attributed to cold condition. Values between −0.5 and +0.5 were considered as the thermal acceptability condition (neutral zone). In the case of hot TSV classes, the range between +0.5 and +1.5 was considered slightly warm, between +1.5 and +2.5 as warm and above +2.5, hot.

Table 2. Thermal stress and sensation levels for the Predicted Mean Vote (PMV) and Physiological Equivalent Temperature (PET) indices [1].

PMV	PET (°C)	Thermal Sensation	Physiological Stress Level
<−3.5	<4	Very cold	Extreme cold stress
−3.5 to −2.5	4 to 8	Cold	Strong cold stress
−2.5 to −1.5	8 to 13	Cool	Moderate cold stress
−1.5 to −0.5	13 to 18	Slightly cool	Slight cold stress
−0.5 to 0.5	18 to 23	Comfortable	No thermal stress
0.5 to 1.5	23 to 29	Slightly warm	Slight heat stress
1.5 to 2.5	29 to 35	Warm	Moderate heat stress
2.5 to 3.5	35 to 41	Hot	Strong heat stress
>3.5	>41	Very hot	Extreme stress to heat

[1] Adapted from [29].

2.7. Shading Performance of Courtyard

To analyze solar shading in courtyard case, Ecotect Analysis software [30] was selected to measure the desired environmental factor. Thus, a three-dimensional model was simulated in the software to obtain the quantitative measures of shading on surfaces and to identify the surfaces of inner courtyard envelop that receive the least shading or most solar insolation (Figure 5).

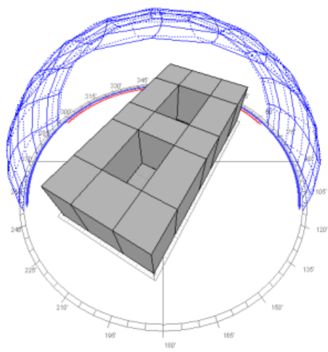


Figure 5. Simplified 3D model of Palácio da Instrução Building.

Shading on the facades/floor depends on the latitude and longitude of the building implantation (solar trajectory), orientation, and form of the courtyard. Thus, the percentage of shading on facades (n = 4) and floor (n = 1) was determined from 6 a.m. to 18 p.m. for the research days. Thereby, the average hourly Shading Index for all surfaces areas inside the courtyard was calculated using Equation (2):

$$I_{shade} = \frac{\sum_{i=1}^{n} (AS_i \cdot HPS_i)}{\sum_{1}^{n} AS_i}, \quad (2)$$

where ASi is the area of surface i of the courtyard; HPSi represents the hourly percentage of shadow on facades/floor surface i of the courtyard. This index was used to help assess the courtyard's thermal performance regarding its Passive Cooling Effect.

2.8. Evaluation of the Thermal Impact Provided by the Courtyard and Its Influence on Thermal Sensation

As diurnal temperature distributions are affected by geographical position, altitude, geographical characteristics, the presence or absence of clouds, solar radiation, and wind speed, among others, the Diurnal Thermal Range (DTR) proposed by Diz-Mellado et al. [31] as a climatic variability index to assess the potential for passive thermal courtyard cooling throughout the day was applied. The DTR is calculated by the difference between the maximum and minimum air temperatures on a specific day, according to Equation (3):

$$DTR\ (°C) = Tmax - Tmin, \quad (3)$$

where Tmax is the maximum temperature and Tmin the minimum temperature. DTRs were calculated for both the courtyard air temperature and the temperature outside of the courtyard.

The potential for passive cooling/heating provided by the courtyard as an architectural element is affected both by its geographical position, orientation, height and dimensions proportions (width and length), and by synoptic weather conditions. The courtyard as a passive strategy is capable of influencing microclimate variables (temperature, humidity, and air speed), as well as radiant temperature and sunshine, and consequently, occupant thermal sensation. Therefore, aiming at identifying the potential impact of this passive strategy, the thermal cooling or heating capacity and the thermal sensation attenuation provided by this environment in two extreme weather conditions were evaluated, comparing the courtyard performance with regard to the external open sky condition in hot and cold measurement days. The thermal impact was estimated using the hourly thermal difference or gap (ΔHT) between outdoor and courtyard air temperature for any time of the day thermal gradient according to Equation (4):

$$\Delta HT = T_{outdoor} - T_{courtyard}, \quad (4)$$

where $T_{outdoor}$ is the temperature of the outside air (sensors on the building roof) and $T_{courtyard}$ is the internal courtyard temperature, with measurements conducted close to the central courtyard region.

The impact of the sensation attenuation was estimated through the difference between the open-air thermal index ($mPET_{outdoor}$) and the thermal index inside the courtyard ($mPET_{courtyard}$), according to Equation (5):

$$\Delta mPET = mPET_{outdoor} - mPET_{courtyard}. \quad (5)$$

The microclimatic variables measured in each environment (in the open sky environment and inside the courtyard) were considered for the thermal sensation derivation by the mPET index, assuming clothing of 0.5 cl for hot days, and 0.68 cl for cold days, comprising average values obtained from surveys for each of these meteorological weather conditions. The days considered in the study were characterized by a low presence of clouds and the absence of precipitation, comprising the extreme standard synoptic conditions that occur in the region. In the conditions adopted herein, solar radiation penetration inside the courtyard was considered, affecting radiant temperature and, consequently, influencing occupants' thermal sensation.

3. Results and Discussion

3.1. Characterization of Personal Variables

The profile of the occupants comprising the sample consisted of predominantly female adults between 25 and 64 years old (Table 3). When considering the parameters established by the World Health Organization (WHO), the BMI analysis (average 25.5 kg/m^2) indicated that overweight people predominated over healthy people in the sample, indicating an overweight trend, previously reported for the Brazilian population [32].

Concerning personal data, the sample was characterized as diverse, covering wide age (14 to 83 years old), weight (49 to 110 kg), and height (1.44 to 1.93 m) ranges (Table 4). Clothing thermal resistance varied from summer (0.2 clo) to winter (1.0 clo). The evaluated average was 0.5 clo, which corresponds to typical clothing used in the region (shirt, pants, and underwear). During the measurement campaigns, on milder temperature days, the average thermal resistance of the interviewees' clothing was 0.68 clo, which corresponds to the typical clothing of the region plus a jacket or coat. In this regard, a behavioral aspect observed in the region indicates that the local population use lower cloth insulation during cold days than those who live in Europe, which is attributed to the absence of adequate clothing insulation for cold stress conditions, since interviewees wore overlapping light clothing during the field campaign [13].

Table 3. Anthropometric data of the population comprising the research sample.

Parameters	Categories	Number of Respondents	Respondents (%)
Sex	Female	46	52.27%
	Male	42	47.73%
Age	Up to 25 years old (young)	36	40.91%
	Between 25 and 64 years old (adult)	46	52.27%
	Over 64 years old (elderly)	6	6.82%
Body Mass Index (BMI = weight/height^2)	Lean	4	4.54%
	Healthy	37	42.05%
	Overweight	30	34.09%
	Obese	17	19.32%

Table 4. Descriptive analysis of the personal data of the population comprising the research sample.

Categories	Age (years)	Weight (kg)	Height (m)	BMI (kg/m^2)	Insulation (clo)
Average	35.6	71.3	1.67	25.5	0.5
Median	30.0	70.0	1.69	25.1	0.5
Max.	83.0	110.0	1.93	37.2	1.0
Min.	14.0	49.0	1.44	17.4	0.2
S.D	16.4	13.4	0.09	4.3	0.2

3.2. Characterization of Microclimate Variables

The microclimate monitoring revealed a wide range of variation in weather conditions (Table 5). Some interviews were conducted during thermally milder days in the region, which explains temperatures below 20 °C. Due to the solar radiation incidence in the courtyard, the radiant temperature was highly changeable. Despite the communication between the courtyard and the external environment through building opening, it appears that the air speed inside is low (on average 0.3 m/s). The lowest thermal stress intensity predicted by the mPET index was observed in winter (21.6 °C), and the highest, in summer (43.6 °C).

Table 5. Descriptive analysis of the monitored climatic variables.

Period	Statistics	Ta (°C)	RH (%)	V (m/s)	Trm (°C)	mPET (°C)
June to February	Average	30.8	45.0	0.3	41.9	34.3
	Maximum	40.4	69.0	1.1	63.1	43.6
	Minimum	19.9	23.0	0.0	23.3	21.8
	Standard deviation	5.1	12.9	0.3	11.6	6.2

3.3. Thermal Sensation Category Calibration

Concerning the local thermal sensation category calibration for the courtyard, the grouped thermal sensation vote (TSV) mean values were correlated with the grouped mean values of the mPET Index for each 1.0 °C of variation, obtained from the microclimate conditions data at the exact moment of the interviews (Figure 6). The angular coefficient was 0.1535, which corresponds to 6.5 °C mPET for each 1.0 MTSV variation. The slope of the trend line is similar to those of the original thermal stress

PET index ranges derived for the European population, but which is currently out of date, indicating a clear difference in thermal perception between populations, confirming the need to adapt thermal sensation categories to the study areas.

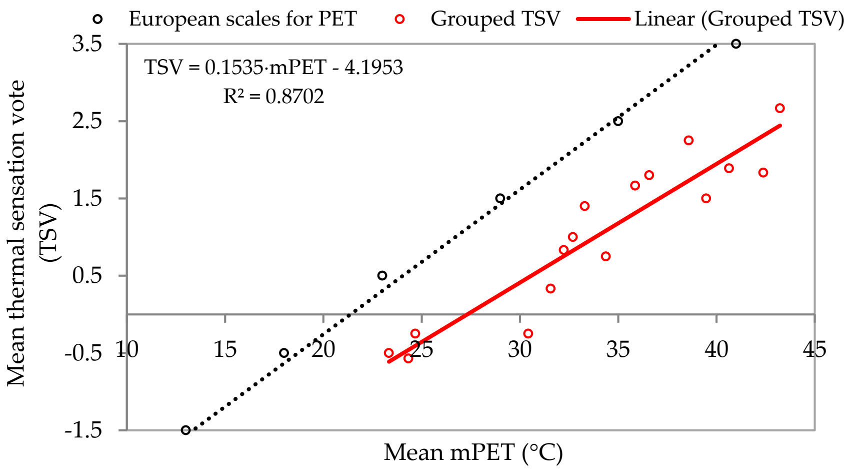


Figure 6. Average thermal sensation votes with regards to the average 1 °C of mPET variation.

By applying the adjustment equation, the Neutral Temperature (VPT = 0) was calculated, in which people feel neither cold nor hot, to be 27.3 °C mPET (no thermal stress), higher than that of the original PET, of 20.5 °C. In studies carried out in a subtropical climate (Cfb) in the city of Curitiba, southern Brazil [33], the PET/ TSV ratio was almost 12 °C/VPT, with a neutral temperature of 19.2 °C. In a study conducted in three cities located in Taiwan (tropical Aw), the slope was 0.1979, which corresponds to 5.1 °C mPET for each 1.0 TSV variation, with a neutral temperature of 28.3 °C [25]. Taiwan's climate is similarly classified as that of Cuiabá, but as local residents have different habits, postures, and thermal adaptations, they present different thermal requirements [34].

The differences concerning what was observed in the south of Brazil are partially associated with the need for the population of that region to acclimatize to wide thermal variations throughout the year, due to more severe winters, which does not occur in the Brazilian tropical region, where high air temperatures prevail throughout the year, with a virtually absent winter, characterized only by milder temperatures. In fact, as a cultural aspect, people yearn for the first cold days of the season, as a form of relief from the constant hot stress conditions [13]. The line derived for the study region is dissimilar to that proposed for Europe at 6.8 °C, reflecting not only local inhabitant acclimatization, but also the influence of the morphological configuration of the physical elements that make up the courtyard and subjective factors [14].

Table 6 exhibits the local thermal sensation categories adapted for the courtyard in the city of Cuiabá derived from the calibration equation presented Figure 3, with the respective original thermal and local stress categories for the city of Curitiba-PR. The calibration ranges for the Tropical Savannah climate when compared to those developed for the Brazilian subtropical climate reveal the discrepancies in climatic adaptations among both populations. It is important to note that the thermal comfort zone for the population of Curitiba (13 to 25 °C) is elastic, due to the climatic variation observed in this region, with more rigorous winters and well-defined seasons. The local thermal neutrality range observed for Cuiabá is more restricted and set at higher temperatures (24.1 to 30.6 °C), due to the climatic rigor of the existing heat, due to the city's geographical position and inhabitant acclimation to the climate. In a study conducted in the southeastern region of Brazil in the city of Vitória-ES [12], the thermal comfort range (22 to 30 °C) and thermal sensation ranges are similar to the derivative for Cuiabá-MT since they are located in the same climatic region in Brazil but not identical. Thus, it is evident that thermal perception is dependent on climatic conditions but also due to behavioral, personal, social, and cultural factors [34]. The local thermal stress categories were used to assess the thermal sensation inside the courtyard, and cold categories were not possible to determine, due to the absence of votes for these categories during the campaigns.

Table 6. Thermal stress categories for mPET and local thermal sensation categories (calibrated) for the courtyard assessed in Cuiabá-MT.

PMV	Thermal Sensation	Original PET	Curitiba PET (Subtropical) [33]	Vitória PET (Tropical) [12]	Calibrated mPET (Tropical Aw)
<−3.5	Very cold	<4 °C	-		-
−3.5 to −2.5	Cold	4 to 8 °C	-		-
−2.5 to −1.5	Cool	8 to 13 °C	-	18 to 22 °C	-
−1.5 to −0.5	Slightly cool	13 to 18 °C	<13 °C	20 to 22 °C	<24.1 °C
−0.5 to 0.5	Comfortable	18 to 23 °C	13 to 25 °C	22 to 30 °C	24.1 to 30.6 °C
0.5 to 1.5	Slightly warm	23 to 29 °C	25 to 37 °C	30 to 34 °C	30.6 to 37.1 °C
1.5 to 2.5	Warm	29 to 35 °C	>37 °C	34 to 46 °C	37.1 to 43.6 °C
2.5 to 3.5	Hot	35 to 41 °C		>46 °C	>43.6 °C
>3.5	Very hot	>41 °C			-

3.4. Courtyard Shading Index

The shading indexes can be visualized in Figure 7. The minimum Ishade of the cold days (at 12 a.m. with 75.24%) did not occur at the same time as the hot days (at 11 p.m. with 65.44%). In turn, the average daily Ishade on the cold days (84.77%) was 6.8% higher than that observed on the hot days (79.38%), which is attributed to the proximity of the winter solstice (July) with different solar trajectories from those on the hot days, with proximity to the equinox (September). From 10 a.m. to 2 p.m. the lowest level of shading index inside the courtyard in both days could be observed.

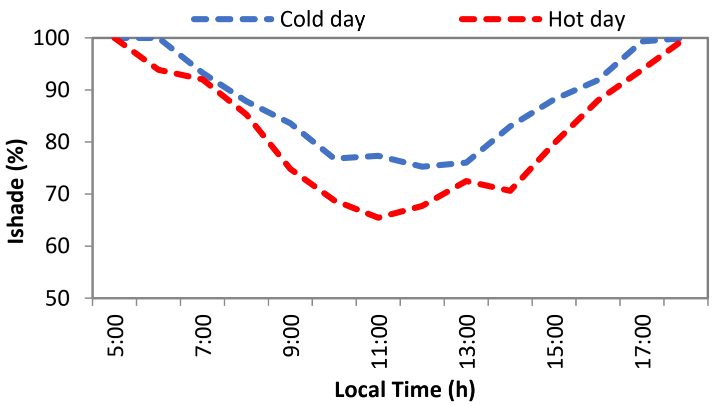
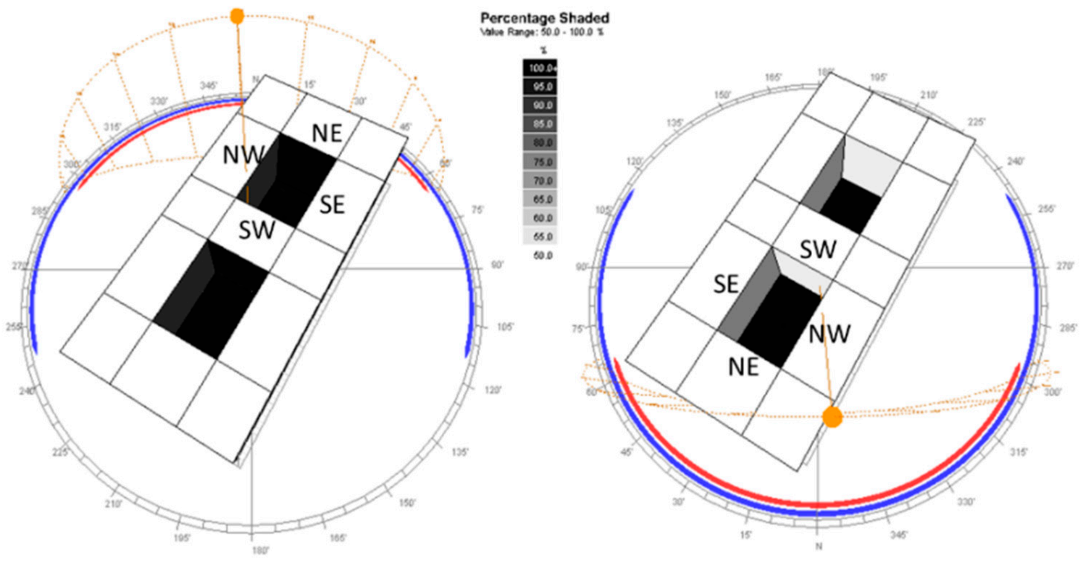
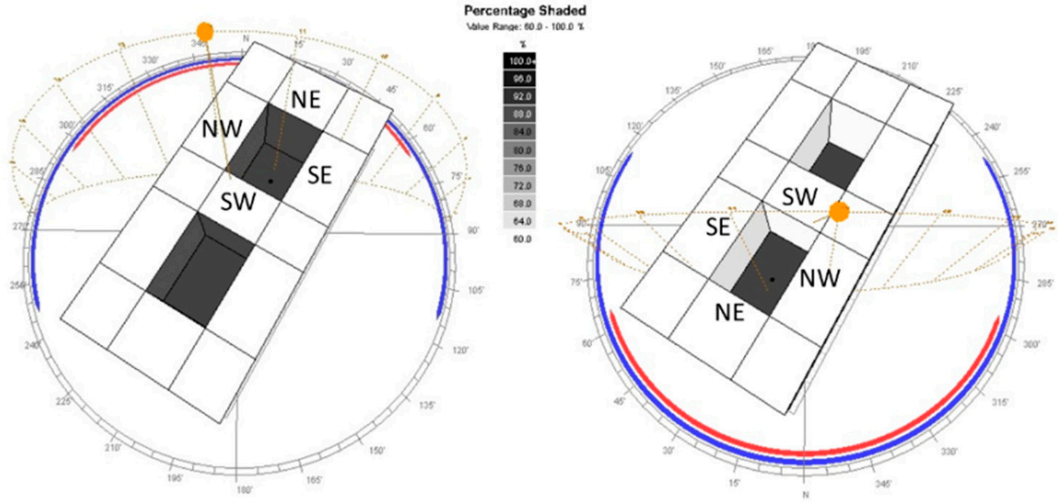


Figure 7. Average of the total shading inside the courtyard's surfaces.

In research days, in the courtyard located in the tropical region, with NE-SW axis orientation, the SW and SE façades were the sunniest surfaces, i.e., with less average shading index during the day. On other hand, the NW and NE façades were the ones less exposed to the sun, with the highest level of shading in its surface. Since the sun was declining to the north on measurement days, the surface of the courtyard's floor remained with a high level of shading throughout the day (Figure 8). The observed patterns are similar to those found for rectangular courtyards during winter and summer solstice, respectively [6]. However, when the sun declines lower than −15.61° (latitude of the building implantation), the previous behavior described for the facades is modified. Thus, regions previously shaded inside the courtyard start to receive insolation, which imposes a careful study on the architectural strategies implementation to improve its environmental performance.



(**a**)



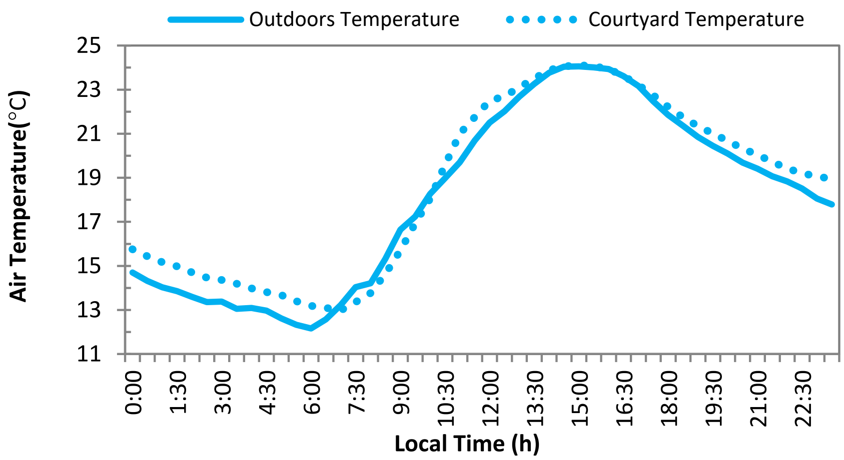
(**b**)

Figure 8. Average daily percentage of shading on the courtyard's surfaces. (**a**) Cold day, (**b**) hot day.

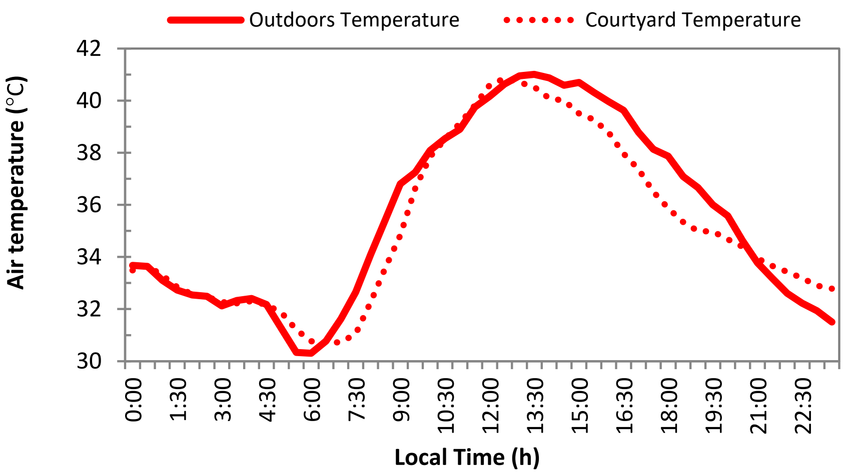
The shading effects on inner surfaces of the courtyard play a decisive role in thermal performance once they directly interfere with the microclimatic conditions of courtyard environments. As there was not much difference between Ishade indexes in the surveyed days, it is not expected that there will be many variations between thermal ranges (DTR) inside the courtyard on cold and hot days.

3.5. Courtyard Thermal Environment Impact

The daily courses of external air temperature and DTR variations are consistent with the synoptic patterns observed in the region during the surveyed months (Figure 9). The DTR on the coldest day was 11.9 °C and on the hottest, 10.7 °C, compatible with the values observed in the climatological normals recorded for the region (9.75–11.6 °C) [35]. The air temperature variation inside the courtyard is linked to the daily outside temperature course. The DTR observed inside it on a cold day (11.10 °C) was slightly higher than that quantified on a hot day (10.10 °C), but both with amplitude very close to that noted on the outside. The daily DTR cycle of the patio is intrinsically related to the level of sunshine and shading provided by its geometric shape and the physical and thermal properties of its internal envelope. Besides this, the nocturnal radiative cooling resulting from the difference between atmospheric and terrestrial longwave radiation is not very pronounced in the region, despite the climatic conditions on both days indicating a clear sky and dry atmosphere. Thus, the low nighttime cooling capacity observed in the present study can compromise the cooling potential of the surveyed courtyard, as described below.



(**a**)



(**b**)

Figure 9. The daily cycle of air temperature inside and outside the courtyard on (**a**) cold day and (**b**) hot day.

Similar thermal gradient behaviors were observed between the surveyed days within the courtyard in the morning period (Figure 9). On a cold and hot day, from 6 a.m. to 10 a.m., the courtyard remained less heated, as a result of the prevalence of shaded surfaces and low insolation intensity received in the courtyard envelope, featuring passive cooling behavior, with greater expressiveness on a hot day compared to a cold day. However, courtyard overheating was noted from 10 a.m. to 1 p.m., due to solar height, with increasing insolation, affecting the facade and floor surfaces, concomitantly reducing shaded areas, less intense on hot days compared to cold days despite the lower level of Ishade in its interior. During this period, cold day behavior was different than hot day performance. In the former, overheating was prolonged during the evening and at night, which is beneficial after a cold front, resulting in higher temperatures and reducing cold stress (Figure 9a). In the latter, passive cooling reestablishment was noted after 1 p.m., alongside decreased in insolation and increased shading due to solar height decreases, extending until 9 p.m., followed by overheating, extending until the early morning (Figure 9b).

The passive heating effect observed on a cold day after a cold front during the afternoon was due to the fact that a portion of the energy received by the courtyard is stored in the form of conductive fluxes, reducing thermal convective exchanges, resulting in the interior air temperature taking some time to reheat. At night, both on cold and hot days, overheating occurs due to the heat stored inside the courtyard and its geometric shape, which receives the released energy and traps the heat inside it, due to multiple longwave radiation reflections, maintaining the air heated for a longer period of time compared to the outside air [35].

On a cold day, except for early morning, the ΔHT analysis indicated a passive heating effect, with mean values of −0.7 °C and a peak of −1.3 °C. The opposite occurred on a hot day, with the predominance of passive cooling, with average values of 1.1 °C and a peak of 2.0 °C, higher than during the morning period of a cold day (Figure 10). This proves that the regulatory thermal capacity provided by the patio is a passive strategy for tropical climate regions in the two extreme weather conditions surveyed herein. For the cold condition, the ΔHT pattern was similar to that identified in cold climate studies, where a passive heating effect has also been reported [36]. However, the ΔHT pattern was different from that observed in Mediterranean climates for hot days, where courtyards display the ability to regulate interior temperatures with increasing outside temperatures, extending throughout the morning, afternoon, and early night. During the hottest times of the day, the attenuation observed in a courtyard similar to the one surveyed herein was over two-fold (4.4 °C) that quantified in the present study [2,9]. This is due to the fact that the internal DTR in the courtyards in this region is, on most days, much lower than the external DTR, due to the high nocturnal radioactive cooling observed in the region. Therefore, the high DTR variation inside the courtyard in a tropical climate is a cooling potential limiter. In turn, overheating inside courtyards has been reported in other studies [36,37], with the form factor attributed as the main performance parameter, since it controls solar radiation and shading throughout the day. This was verified herein, where a positive cooling effect with decreasing insolation and increased shading in the courtyard envelope were observed.

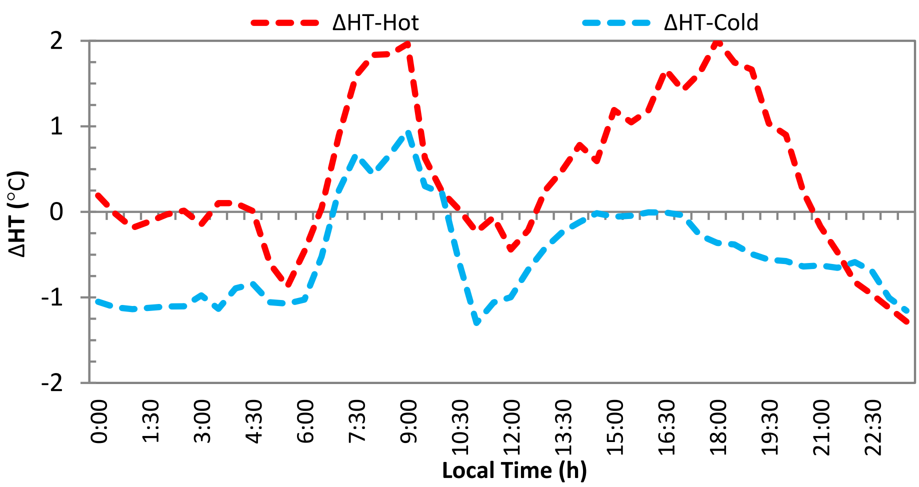


Figure 10. Hourly thermal gap (ΔTH) between the outdoors and internal courtyard temperature.

The daily thermal sensation cycle in the open sky condition is strongly dependent on the incidence of solar radiation, since this is the main variable responsible for altering the radiant temperature received by bodies (Figure 11). Thermal sensation is affected not only by microclimate variables but also by the shading and solar radiation received on facades and floors, resulting from the courtyard's solar orientation, geometric shape, and solar trajectory throughout the day. This dynamic interferes with the shaded areas in the facades/floor, as described before, and consequently the irradiation of the internal surfaces, affecting interior courtyard radiant temperature. At certain times (10 a.m. to 2 p.m.), the thermal sensation becomes even higher than the open sky condition, due to both the solar incidence and irradiation of internal courtyard surfaces due to reduced Ishade in its interior. When a preponderance of shading and low insolation inside the courtyard is noted (morning until 10 a.m., afternoon from 2 p.m., and night, Figure 11), the thermal sensation is more dependent on other environmental variables, since radiant temperature approaches air temperature.

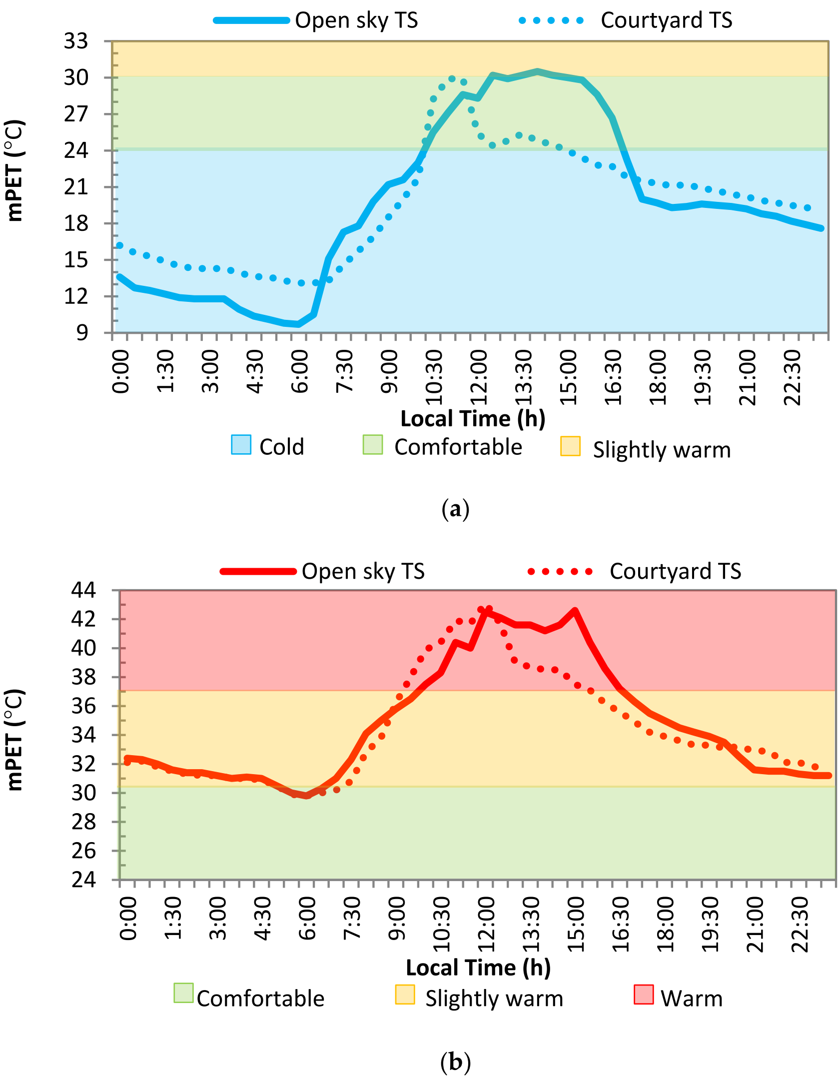


Figure 11. Daily thermal sensation cycle inside and outside the courtyard on (**a**) cold and (**b**) hot day.

On a cold day, a "thermal comfort" sensation (24.1 to 30.6 °C) was noted between 10:30 a.m. and 2:30 p.m., due to the rise in the radiant temperature provided by the greater insolation inside the courtyard. At other times, the thermal sensation was "cold" (<24.1 °C), although this is milder than that observed in the open air (heating effect). On a hot day, the feeling of "thermal comfort" was only achieved in the early morning, from 5 a.m. to 7 a.m. A "slightly warm" sensation (30.6 to 37.1 °C) was perceived inside the courtyard until 10 a.m., the time when the radiant temperature rises, with a "warm" sensation (37.1 to 43.6 °C) until 4 p.m., due to the reduction and approximation of the radiant temperature to the air temperature. From then on, until dawn, the feeling inside the courtyard remained "slightly warm". As these were extreme days, the percentage of comfort hours in the courtyard was low, both on a cold day (16.66%) and on a hot day (8.33%).

On a cold day, during the night (from 6 p.m. to 6 a.m.), courtyard overheating was noted, which resulted in a higher thermal sensation than on the outdoors (on average −2.2 °C) (Figure 12). During the morning and afternoon periods, except for the greatest interior courtyard insolation period, when an increased thermal sensation was noted (on average −2.3 °C), it was possible to observe that passive courtyard cooling capacity is capable of influencing open sky thermal sensation (3.8 °C reduction). On a hot day, night behavior was similar to the cold, with decreased night heating, and consequently stabilization of the difference in the thermal sensation between the external and internal environments. An increase in the sensation inside the courtyard during the greatest solar incidence period (on average −1.5 °C) was also verified. However, the cooling effect influenced both the morning and afternoon, as well as the night (on average 1.7 °C). The thermal sensation attenuation peak was 6.4 °C on a cold day and 5.0 °C on a hot day, both in the afternoon, during the greatest solar incidence periods. Therefore, in general, in the morning and the afternoon, courtyard proportions attenuated thermal sensation conditions in relation to external ones. However, during the greatest solar exposition hours (10 a.m. to 2 p.m., with reduced Ishade index), the increased thermal sensation was observed, even if the geometric courtyard proportions are indicated as ideal for the region, due to solar radiation penetration into the courtyard environment. Despite this, the geometric proportions of the studied courtyard were able to provide a stabilizing effect on the indoor thermal comfort, raising the thermal sensation during the greatest cold stress period (on cold days) and reducing it during greatest heat stress periods (on hot days). This trend was observed for courtyards located in a Mediterranean climate, where increased aspect ratio reduced extreme thermal stress values to both cold and heat estimated through the PET index, with more pronounced effects in summer than in winter [11]. Thus, the use of this passive architectural cooling or heating strategy for tropical climates is noteworthy, due to courtyard capacity to attenuate the thermal sensation of its users in relation to open-air environments.

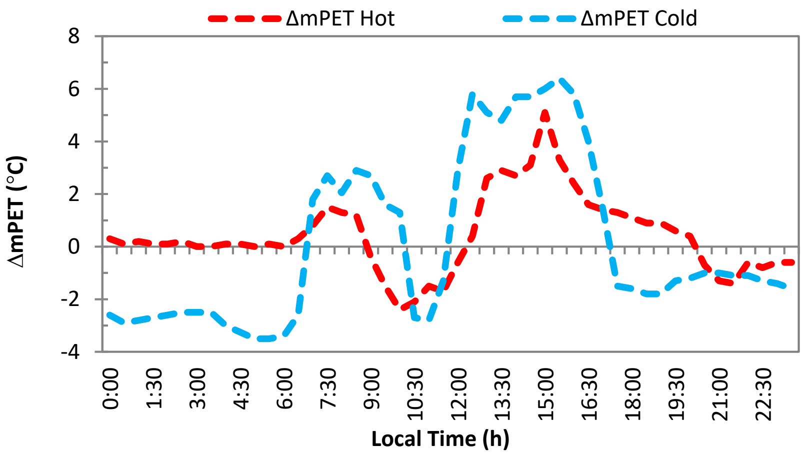


Figure 12. Courtyard thermal sensation attenuation with regards to the open sky condition.

Based on the previous results, regarding the courtyard's use by the population that frequents it, as a general recommendation for cold days, it is advisable to perform outdoor activities within the courtyard from 10 a.m. to 3 p.m., when solar radiation penetrates the courtyard, reduces shading areas of courtyard's surfaces raising the thermal sensation to within a thermal comfort range. On the other hand, on hot days, the recommendation is the opposite, with outdoor activities inside the courtyard recommended before 10 a.m. and later, at 4 p.m. The presence of vegetation and strategically positioned shading devices are required due to courtyard insolation levels from 10 a.m. to 4 p.m., to make activities accessible at these times. These recommendations are compatible with those presented for courtyards in tropical climates in the northern hemisphere [6].

4. Conclusions

Courtyards are architectural elements used in different regions and cultures to provide an open and protective environment for the user's interaction. This study aimed to investigate the bioclimatic response of a courtyard from the perspective of thermal variations imposed by the tropical climate of the Savanna type (Aw), in extreme cold and hot conditions. The results indicate that the courtyard can be used as a passive strategy for both heating and thermal cooling in the region.

During the cold days, temperatures inside the courtyard remained higher than in the open sky conditions (passive heating effect) during the night, providing a more comfortable thermal sensation than in the external environment, outside the building. During the day, except for the greatest radiation incidence periods within the courtyard, although temperatures remained higher than the outside (again, due to a heating effect), due to courtyard shape factors and solar orientation (which interfere with its internal shading), the courtyard was able to attenuate user thermal sensation at an average of 3.8 °C and peak of 6.4 °C, producing a thermally milder environment with regard to open sky conditions, with a sensation ranging from cold to thermal comfort.

During hot days, the most frequent condition during the year in the research region, the courtyard proved to be an adequate strategy to mitigate thermal conditions. Again, except for the highest solar radiation incidence hours and a few hours during the night, the courtyard was able to act as a passive thermal cooling system, lasting for a few hours during the night. Consequently, an average of 3.8 °C on thermal sensation attenuation inside the courtyard was observed, with a greater impact during the afternoon, peak reduction of 5.0 °C, when the highest air temperatures are displayed. It was verified that in the extreme conditions, the percentage of comfort hours is low, both on cold (16.66%) and hot (8.33%) days. Based on these findings, courtyards may be an alternative as a climate-responsive design strategy to counteract the overheating effect in buildings due to the impact of climate change.

As a general rule, recommendations for courtyard use for outdoor activities are antagonistic. For cold days, the courtyard should be used during the greatest insolation periods, i.e., with the lowest level of shading in the courtyard's surface, to reduce thermal cold sensations. On the other hand, on hot days, one should avoid using the courtyard at these times, preferably using it during early morning and at the end of the evening. Vegetation and shading are recommended to promote shading on hot days but should be strategically positioned and designed to provide sun exposure areas for cold days because sun declines lower than the latitude of the building implantation.

For improving courtyard performance in a tropical climate, the incident solar radiation should be controlled in the courtyard on hot days, since insolation on the facades and floors increases air and radiant temperature inside the courtyard, degenerating not only the passive cooling effect but also the attenuation of the thermal sensation provided by this architectural strategy. Although courtyards are beneficial during cold days, since they contribute to increased air temperatures and, consequently, the attenuation of cold thermal sensations, as the cold front frequency is low in the study area, courtyards in the assessed climate region should be designed in such a way to contribute to decreasing the high heat thermal stress conditions in these areas.

Thus, architectural improvements may be indicated to reduce the increasing in the superficial temperature in the courtyard's envelope. For this purpose, for the facades it is recommended to use light colors in order to reduce thermal gains as well as the use of green envelopes (green walls). For floors, it is recommended to maximize permeable areas with the planting of small native vegetation/shrubs or grasses. For the dry season, irrigation to vegetation must be provided because of the decline in rainfall. The installation of permeable or cool pavements is also recommended, since it has a network of interconnected voids that allows water to infiltrate into the underground, thus allowing part of the energy received by solar radiation to be used to evaporate the water stored internally and below the paving, reducing heat sensible fluxes, which results in a cooling effect on the paving. To provide a space for users to remain, it is recommended to install pergolas covered with vegetation in order to reduce the incidence solar radiation on hot days. In this way, these architectural improvements may provide a thermally more pleasant environment for their occupants, thus favoring the development of social and leisure activities within these constructions.

Author Contributions: Conception, design and execution of experiments—I.J.A.C.; methodology—I.J.A.C., C.G.-M. and L.C.D.; formal analysis—C.G.-M. and L.C.D.; writing—I.J.A.C. and L.C.D.; reviewing and editing—C.G.-M. and E.D.-M.; visualization—E.D.-M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Brazilian National Council for Scientific and Technological Development (CNPq), grant number N. 128291/2019, by the National Government of Spain Research Projects (RTI2018-093521-B-C33); and by the Spanish Ministry of Education, Culture and Sport by a pre-doctoral contract granted (FPU 18/04783).

Acknowledgments: The authors would like to thank the State Department of Culture, Sport and Leisure of the State of Mato Grosso /Brazil for authorizing this research and the Federal Uuniversity of Mato Grosso and the Sevilla University in supporting this research. The authors thank the financial support of the Spanish Ministry of Education, Culture and Sport via a pre-doctoral contract granted to Eduardo Diz Mellado. (FPU18/04783).

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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