Contrasting the Passive Cooling Effect Produced by Courtyards Located in the Tropical and Mediterranean Climates

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ABSTRACT: Courtyards are traditional architectural elements applied in many regions of the planet. In this research, the passive cooling potential provided by two courtyards with similar shapes, located in different climates types (Tropical and Mediterranean) were investigated. We focus to identify physical and climatic factors that influence the courtyard passive cooling system under similar weather conditions (in hot-dry period) but in different geographic positions. Shading and Insolation were quantified by computational analysis and thermal indexes determined by monitoring campaigns, focusing to contrast the courtyards performance. Due to differences in the latitude and longitude (solar trajectory), orientation, form and period of analyses, the courtyard located in the tropical region had its internal envelop more shaded and with less insolation than that in the Mediterranean. In turn, as nocturnal radioactive cooling is less pronounced in the tropical region, the outdoor and courtyard diurnal thermal range (DTR) presented lower thermal amplitudes than those in the Mediterranean. As consequence, the average daily difference between outdoors and indoors temperature (ΔT) was lower in the tropical region (1.2℃) than in the Mediterranean (2.5℃). This research confirms the courtyard architectural utility as a passive cooling system for tropical climate, with less cooling effects than those deployed on Mediterranean climate.
KEYWORDS: Courtyards monitoring, Tempering effect, Passive cooling strategy

GLOSSARY			
AR	*Aspect ratio parameter*	$I_{shading}$	*Average hourly shading index*
CT	*Courtyard temperature*	$I_{isolation}$	*Average hourly insolation index*
CDTR	*Thermal amplitude in indoors courtyard air temperature*	*ODTR*	*Thermal amplitude in outdoors air temperature*
DTR	*Diurnal thermal range*	*CTMOT*	*Courtyard temperature at MOT*
MOT	*Maximum outdoor temperature*	*OT*	*Outdoor temperature*
T_{min}	*Minimum air temperature*	T_{max}	*Maximum air temperature*
ΔT	*Thermal difference*	ΔDTR	*Difference between outdoor and indoor thermal amplitude*

1. INTRODUCTION

This study deals with the potential of the courtyard as a project resource to mitigate the effects of climate change and the phenomenon of the Urban Heat Island (ICH) in an urban environment [1, 2].

The courtyard is an enclosed space, open to the sky and bounded by buildings in its perimeter [3], an architectural element commonly applied to increase daylight inside buildings as well as to attenuate the heat gain by shading the external surfaces, offering an internal private space for occupant's interaction [4]. It acts as a microclimate modifier due to its ability for control ventilation and the humidity inside buildings [5], by the arrangement and proportion of full and empty volumes created by its shape. Therefore, its passive cooling potential is an important factor to consider because it may reduce the building's temperature without resorting to the artificial mechanical system which may contribute to resilience to the urban heat island phenomenon, therefore also being beneficial for the mitigation of the global warming [6].

Based on literature review, it turns out that investigations are concentrated on dimensions/aspect ratio of the courtyard (height, width and length, and its proportions) [3, 6, 7], solar orientation once its direct impacts on shadows produced on the external surfaces and solar radiation received [2, 4, 8], the influence of the size of the floor which is generally determined

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according to the latitude of the courtyard [2], the vegetation influence [9], measurements of a courtyard's climatic conditions (air temperature and humidity, ventilation) and their impact on outdoor and indoor thermal comfort [3, 6, 10], buildings energy consumption [11, 12] and theoretical researches using ENVI-met/ Energy Plus software to computational simulations [12, 13].

The Courtyard is a traditional resource commonly used in warm-climate of Desert and Mediterranean cities [2, 4, 6]. In recent years, the interest in the microclimatic courtyard thermal has increased in hot-dry and Mediterranean, but especially in hot-humid and cold climates [3, 11]. Some general rules to design an efficient courtyard regarding height and orientation have been stated for this climate: for Hot-Dry, optimum courtyard height is two-store and the best orientation is the N-S axis but the NE-SW axis would be recommended; for Temperate, two-store and N-S axis; for Cold, one-store and the N-S axis; and for Hot-Humid, three-store and NE-SW axis [3].

Although there is already deepening knowledge about the thermal potential on arid and Mediterranean climates, studies on courtyard thermal performance in hot and warm-humid climates are still incipient, especially in Brazil, in which this architectural element was brought by the Portuguese colonization process. Thus, the objective of this research is to compare the thermal passive cooling potential provided by two courtyards with similar shapes, located in two different types of climate (Tropical and Mediterranean). We focus on identifying physical and climate factors that influence the passive cooling system capacity of the courtyard under similar weather conditions (in hot-dry period) but in different geographic positions.

2. MATERIALS AND METHOD

2.1 Research Locations

The first building is located in the central-western region of Brazil, in the Cuiabá city downtown area with high urban densification (15° 35' 56''S 56° 5' 42''W, 146m a.s.l), characterized by the tropical climate (Aw - Köppen-Geiger classification). The second is located in the southern region of Spain, in the Seville City suburban area with high compactness and low-height edification (37°16'59.39"N 5°55'53.10"O, 58m a.s.l), characterized by a moderate Mediterranean climate (Csa - Köppen-Geiger classification).

The pattern of air temperatures at the locations of the courtyard studied is indicated in Figure 1 [14, 15]. The Aw climate is characterized by a hot and humid season between spring and summer (October to April) and a hot and dry season between autumn and winter (May to September) [16]. The Csa climate presents well-defined seasons, with minder winter and hot summer [3]. From June to August, the air temperature maximum and the minimum monthly pattern is quite close, but the daily courses of the Diurnal Thermal Range (DTR) are different (see section 2.3.1).

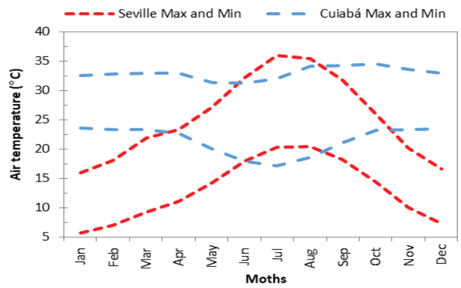

Figure 1: Months mean maximum and minimum air temperatures for Cuiabá/ Brazil and (b) Seville/ Spain.

The buildings' selection followed the general rules established for efficient courtyard described by Rodríguez-Algeciras et al. [3]. Thus, as a preliminary criterion, buildings should present proportionality between its internal courtyards and be oriented following the preferential axis to achieve an efficient performance. The proportions were calculated by using the Aspect Ratio Parameter (AR) [6] by Equation 1:

$$AR = hmax / W \qquad (1)$$

where - *hmax* - maximum height, in meters;
W - is width/ length of the courtyard.

In Aw climate, it was selected an institutional building constructed in the early 19th century, featuring historic-eclectic style with two-store and two central courtyards orientated along NE-SW axis (60°), inner dimensions of 13.7x10x11.8m (width x length x height) (AR equal to 0.81 and 1.43). In Csa climate, a school building, with three-store and three inner courtyards orientated along E-W axis (-6°), inner dimensions of 13.2x 7.5x 10.7m (AR equal to 0.84 and 1.18) (Fig. 2b).

(a)

(b)

*Figure 2: Buildings and its courtyards at (a) Cuiabá/ Brazil (*fuzuedasartes.blogspot.com/2019/10/*) and (b) Seville/ Spain.*

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2.2 Monitoring Campaigns

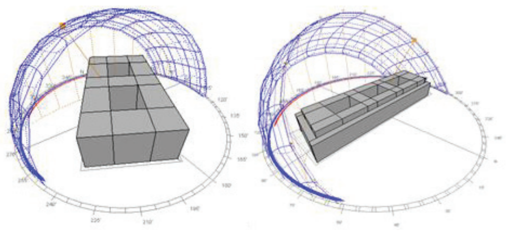
The methodology followed the protocol established by [13], with two weeks of climates variables monitoring inside the courtyards in both surveyed regions. Only days with stable conditions were selected for the analyses, with similar patterns of wind speed and sky conditions featuring typical local seasonal characteristics. The period selected for Aw and Csa climate was from August 28 to 30 (winter season in the southern hemisphere) and June 14 to 21 (summer season in the northern hemisphere), respectively. Despite season's differences, the comparison is feasible once weather conditions are similar in terms of maximum and minimum temperatures, characterized by hot and dry conditions in regions (Fig. 1).

Air temperatures and humidity inside the courtyards were recorded using sensors properly calibrated. To avoid overheating due to solar radiation, the sensors were protected by shields (made of wood or aluminum foil). Outdoor temperatures and wind velocity were also recorded through a meteorological station placed in the rooftop of each building.

2.3 Data Analysis of courtyards

2.3.1 Shading and Isolation performance

It was selected the Shading and Insolation Indexes to contrast the courtyard's performance. The first represents the average percentage of the total courtyard's area shaded (ranging between 0-1), and the second, the average level of insolation received by surface area exposed to the sun inside the courtyard, measured in Wh/m^2. The Ecotect Analysis software [17] was utilized to simulate and obtain a quantitative measure of shading and insolation on the surfaces of inner courtyard envelops (Fig. 3).



(a) (b)

Figure 3: Simplified 3D model of (a) Cuiabá and (b) Seville courtyard (Font: Ecotect Software building modelling)

Shading analyses were carried out during the total campaign period as they only depend on the latitude and longitude of the building implantation (solar trajectory), orientation, and form of the courtyard. Since standard climate file is an alternative strategy to model solar radiation for the researched cases, Energy Plus Weather Files (EPW) were converted into Weather Data Files (WEA) to evaluation the Isolation Index. A specific standard day in the weather data file (Figure 4) inside the measurement period displaying clear sky conditions pattern was chosen to perform solar incidence on surfaces in each region. Since measurements were conducted in different seasons, courtyards located in the north and south hemisphere are under different total solar radiation and photoperiods.

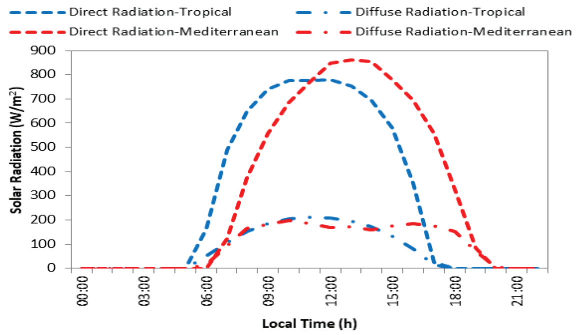


Figure 4: Solar radiation considered for tropical and Mediterranean region (Font: https://energyplus.net/weather*)*

The percentage of shading on the four facades and floor was determined from 6am to 6pm for the building located in the tropics and from 7am to 9pm for the Mediterranean. Thereby, the average hourly shading Index for all surfaces areas inside the courtyard was calculated using Equation 2:

$$I_{shading} = \frac{\sum_{i=1}^{n}(AS_i \cdot HPS_i)}{\sum_{1}^{n} AS_i}) \qquad (2)$$

where AS_i - area of surface *i* of the courtyard;

HPS_i - hourly percentage of shadow on facades/ floor surface *i* of the courtyard.

The average hour of incident solar radiation received in each surface (Wh/m^2) weighted by the percentage of courtyard surface areas hit by radiation was utilized to measure the average hourly insolation index received inside the courtyard by the Equation 3.

$$I_{isolation} = \frac{\sum_{i=1}^{n}(SRI_i \cdot HPRS_i \cdot AS_i)}{\sum_{1}^{n} AS_i}) \qquad (3)$$

where SRI_i - solar radiation intensity on the surface *i* of the courtyard;

$HPRS_i$ - hourly percentage area of radiation received by facades/ floor surfaces *i* of the courtyard*;*

AS_i - area of surface *i* of the courtyard.

2.3.2 Passive Cooling indexes

Since the diurnal cycle of air temperature is affected by geographic position, altitude, geographical features, clouds presence (absence), solar radiation, wind speed, among others, it was utilized the Diurnal Thermal Range

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(DTR) as an index to assess the courtyard thermal potential passive cooling, expressed by Equation (4):

$$DTR\ (°C) = T_{max} - T_{min} \qquad (4)$$

where T_{max} - maximum air temperature (◦C);
T_{min} - minimum air temperature (◦C).

Thermal difference (ΔT) or gap between outdoor and courtyard air temperature for any time of the day was evaluated according to Equation (5):

$$\Delta T = OT - CT \qquad (5)$$

The courtyard efficiency in terms of passive cooling effect was calculated by ΔT_{MOT} (Equation 6), which represents the difference between maximum outdoor (MOT) and courtyard temperature at this moment:

$$\Delta T_{MOT} = MOT - CT_{MOT} \qquad (6)$$

It was also calculated ΔDTR (Equation 7) since ΔT_{MOT} only establishes a specific parameter within a daily cycle of air temperature:

$$\Delta DTR = ODTR - CDTR \qquad (7)$$

where *ODTR* - difference between maximum and minimum outdoors air temperature (◦C);
CDTR - difference between maximum and minimum indoors courtyard air temperature (◦C).

3. RESULTS AND DISCUSSION

The shading index can be visualized in Figure 5. As courtyard shapes are similar, differences are attributed not only to the buildings solar orientation but also due to solar trajectories arising from the fact that seasons are different. Thus, the courtyard located in the tropical region (orientated along the NE-SW axis) provided diurnal higher shading indexes than that located in the Mediterranean (oriented E-W axis). The minimum $I_{shading}$ of the tropical courtyard (at 11am with 62.86%) does not occur with the peak of sunlight incidence while in the Mediterranean does (at 2pm with 50.08%).

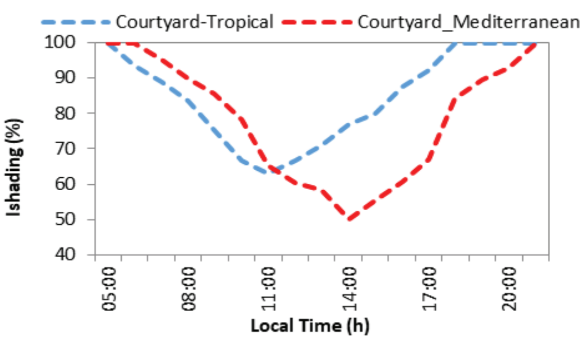

Figure 5: Average total shading on the courtyards' surfaces.

The average daily $I_{shading}$ in building located in the tropics (78.78%) is 6.7% higher than that observed in the Mediterranean (73.77%). The lower average daily shading is also attributed to the proximity of summer solstices in Mediterranean but also the photoperiods once it displays three more hours of sunlight. The daily shading of the Mediterranean courtyard features similar behaviour to those observed in the city of Kerman, Iran (latitude 30°15N) during June, with a minimum shading index equal to 55% [2].

In the courtyard located in the tropical region, the SW and SE façades are the sunniest surfaces during the day. For the courtyard in Mediterranean region, the N and E/W facades are the most exposed. In turn, the courtyards floors receive the second most intensities of insolation in both locations. The observed patterns are similar to those found for rectangular courtyards during winter and summer solstice, respectively [3].

The insolation index follows a similar behaviour for the shading index. The $I_{insolation}$ peak in the courtyard at Tropical and Mediterranean region reaches 153.3Wh/m^2 at 10am and 162.3Wh/m^2 at 2pm, respectively. The average daily insolation received in the Mediterranean courtyard was 85.5Wh/m^2, only 1.7% higher than the tropical region (84Wh/m^2) (Fig. 6). The similar intensities are due to the differences observed in the photoperiod in the researched regions. The total solar radiation gains by courtyard in the Mediterranean summer day (1116.1Wh/m^2) is 12.6% higher than the tropical winter day (1008.50Wh/m^2), compatible with the intensities observed for the direct and diffuse solar radiation between the standard days chosen to conduct the insolation analyses. The last value is compatible with those observed in a rectangular oriented NE-SW axis courtyard in the city of Camagüey-Cuba for the winter solstice [3].

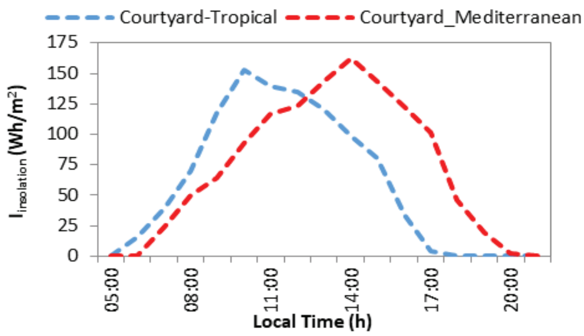

Figure 6: Average total isolation on the courtyards' surfaces.

The combination of shading and insolation effects on inner courtyard surfaces plays a decisive key to thermal performance once they directly interfere in the microclimatic courtyard conditions. Since the inner

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envelope of the tropical courtyard is more shaded and under lower intensity and range of solar radiation, it is expected Diurnal Thermal Range (DTR) lower than those located in Mediterranean. However, the physical and thermal properties of the inner courtyard envelope may also influence its passive thermal performance.

The daily outdoor air temperature variation and DTR are consistent with the synoptic patterns observed in both regions (Fig. 7). Winter measurements in the tropical region were carried out during a period of scarce rainfall and absence of cold fronts entrance what justifies the high air temperature recorded. Summer measurements at the Mediterranean also displayed high air temperatures, with minimum temperatures reaching values much lower than those in the tropical.

The indoor courtyard temperatures are linked to the daily course of external temperature and the shading and insolation penetration inside the courtyard. The indoor temperatures in the Mediterranean courtyard always remain lower than the outdoor. In the tropical region, the pattern is similar but during the period of the highest insolation, the indoor temperature almost reaches the outdoors. In turn, the minimum indoor temperatures are always higher than those observed in the Mediterranean region. The tropical courtyard behaviour is related to its geographical location which is characterized by high air temperatures but also due to the lower radiative cooling capacity provided by atmospheric conditions during night-time.

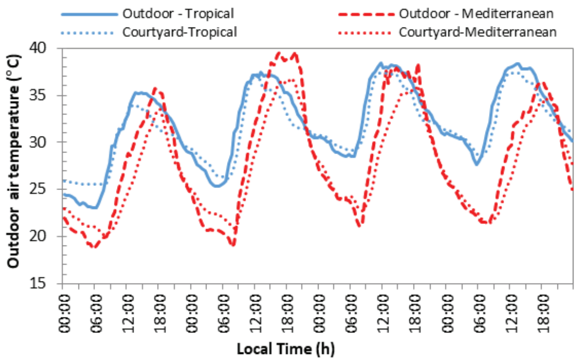

Figure 7: Daily course of outdoor and indoor courtyards' air temperature during the campaigns.

The distribution patterns of outdoors DTR in the tropical region displayed low range (10-12.2°C) when compared to those observed in the Mediterranean (15-20.7°C) and both are compatible with the climatological normal data of its regions [14, 15]. The indoor DTR range for the tropical region (8.20-10.7°C) is close to that observed outside, while in the Mediterranean region it is smaller (12.3-15.4°C). The DTR daily cycle is related to the radiation level received by each region, which is reduced in the tropical region because of the lower insolation received during the winter and higher in the Mediterranean region, due to the summer period. Indoors DTR has also coupled with courtyard physical and thermal properties, affecting it.

During night-time, nocturnal radiative cooling resulted from the difference between atmospheric and terrestrial longwave radiation, is more pronounced in Mediterranean than in the tropical region despite weather conditions in both regions present clean sky and dry atmosphere, factors associated with scarce rainfall and a dry period lasting 4–5 months. Thus, the lower night-time cooling rates observed in tropical regions may compromise the cooling potential effect.

During the daytime, it is possible to observe dropping in the air temperature inside the courtyard in both buildings, confirming the researched bioclimatic passive strategy can moderate the outside air temperature (Fig. 8). During the period of highest insolation inside the courtyard in the tropics (from 10 am-1pm), the indoor air temperature rises, almost reaching the outdoor temperature. This behaviour differs from that observed in the Mediterranean region, since the courtyard can moderate the external air, especially in the warmest part of the day. This cooling effect extends until 9pm at night-time. Thenceforth until early morning, due to courtyard geometrical form (sky view factor) and the façade's physical and thermal properties, it is observed an overheating effect caused by longwave radiation multiple reflections that keep the courtyard environments warmer than the outside.

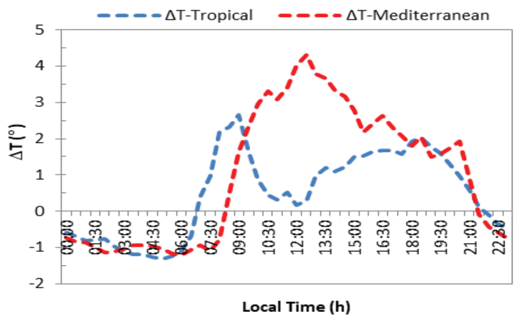

Figure 8: Mean daily thermal differences inside the courtyards.

The maximum ΔT_{MOT} in the tropics region (2.65°C) occurs before the peak of outside air temperature and insolation inside the courtyard. It is quite lower than those observed in the Mediterranean (4.3°C), with a peak near the maximum thermal and insolation records. The average daily ΔT is twice as much in the Mediterranean region (2.5°C) than in the tropical region (1.2°C). The moderating effect observed is intrinsically related to the net difference between the outdoor DTR and the courtyard DTR. The ΔDTR range is small (1.7-3.8°C), reducing the potential passive cooling

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effects in the tropical region. In turn, in the Mediterranean, it is upper (2.7-5.3°C), allowing passive cooling to be more substantial.

Based on the factors previously described, it can infer that the outdoor DTR variations significantly influence the thermal regulation provided by the courtyard as a passive architectural design strategy. Thus, the tempering capacity of the courtyard located in tropics is less effective than in Mediterranean. It is important to state that physical and thermal properties of inner courtyard envelope were not taken into account in the analyses. However, its effects have been captured during the campaigns, influencing ΔT and the inner thermal amplitudes of the courtyard DTR.

4. CONCLUSION

The current research focuses on contrasting the thermal performance of two courtyards located in different climates, aiming to understand the microclimatic interactions that interfere in the passive cooling effects in two similar geometrical courtyards located in distinct climates. The findings confirm the courtyard as a passive cooling system in tropical climate under hot and dry season, but with less cooling effects than those deployed on the Mediterranean climate.

The study of shading and insolation allowed demonstrating that these indicators affect the courtyard thermal environment in a different way at each region. Due to the differences in the latitude and longitude (solar trajectory), orientation, form, and period of analyses, the courtyard located in the tropical region had its internal envelop more shaded and with less insolation than that implanted in the Mediterranean. Along with the fact that nocturnal radioactive cooling is less pronounced in the region, the outdoor and courtyard DTR presented lower thermal amplitudes than in the Mediterranean, decreasing the courtyard cooling potential in the tropical regions. In turn, due to a higher nocturnal radioactive cooling effect, despite less shading on the envelope and highest insolation in the summer, it was observed higher outdoor and courtyard DTRs, allowing the cooling effect to be more effective in the Mediterranean courtyard.

Due to limitations of using only one courtyard per climate, it becomes necessary to contrast courtyards with different geometric form in both regions to enable the enhancement of research findings.

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