Building and Environment 203 (2021) 108094

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Extending the adaptive thermal comfort models for courtyards

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ARTICLE INFO

Keywords:
Climate resilience
Microclimate
Adaptive thermal comfort
PET
Comfort data interpretation
Courtyards

ABSTRACT

Temperatures in Mediterranean cities are rising due to the effects of climate change, with a consequent increase in the heat waves frequency. Recent research has shown the tempering potential of semi-outdoor spaces such as courtyards, which are semi-enclosed spaces that are widely used by the users of buildings in Mediterranean cities. International standards addressing thermal comfort parameters provide technical guidelines for indoor spaces only. Expanding this concept, this paper focuses on the potential to extend and interpret the existing calculation models for indoor thermal comfort, EN 16798 and ASHRAE 55, to determine thermal comfort, monitoring two different courtyards in Cordoba, Spain, during both typical summer and heat wave periods. The results show that during the typical summer, the monitored courtyards can reach temperatures up to 8.4 °C cooler than outside. Subsequently can be considered to be in thermal comfort on average for 88% of the time according to EN 16798, and 75% according to ASHRAE 55, which drop to 71% and 52% respectively during heat wave (HW) periods, in spite of increasing thermal gap (TG) up to 13.9 °C. The results are also compared with the PET indicator used for evaluation of outdoor thermal comfort, which provides comparable figures: 81% summer and 73% HW. Implications of implementing passive shading strategies to increase comfort in these transition spaces are also evaluated. The research highlights the thermal potential and usefulness of courtyards in warm climates, so they can ultimately be included in the building analysis as a potentially comfortable and habitable space.

1. Introduction

The increase in global average temperatures has become a major issue in recent decades, as well as the human perception and adaptability considering air quality and comfort temperatures [1]. The gloomy forecasts indicate the impact of frequent heat waves in southern European locations. It is expected that the densified city centres will suffer the greatest consequences due to the urban heat island effect (UHI) [2]. Historically, human beings could modify the surrounding environment to improve their daily life, facilitating their adaptation to this environment [3]. Taking into account the forecasts for the impact of global warming by the end of the century in cities in Southern Europe [2] comfort standards must be adapted, anticipating the scenario of increasingly hot urban environments.

The basis for the adaptive thermal comfort theory reflects the real adaptive capacity of humans in different thermal environments with the appropriate behaviour to avoid discomfort [4]. Each individual can interact with the environment, gradually adapting to it [5]. The adjustment of the activity that is being developed, or aspects related to adaptation such as psychological or physiological are some of the categories defined by other researchers [6]. Previous studies based on surveys carried out in European countries show the relationship between indoor comfort and outdoor temperature in buildings in free-running mode, with the indoor comfort temperature increasing along with the outdoor temperature [7]. This is not the case in HVAC buildings [8], where the thermal environment is strictly controlled; so thermal comfort is greatly influenced by the architectural design of buildings, the building services, and their operation [9]. Taking into account the users' comfort, quantifying the energy required to make buildings comfortable has a direct impact on the environment [6]. In outdoor environments, these have been analysed in terms of their thermal comfort and suitability [10], the social and economic impact on certain cities [11], as well as aspects related to the health level of the

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https://doi.org/10.1016/j.buildenv.2021.108094
Received 23 April 2021; Received in revised form 22 June 2021; Accepted 23 June 2021
Available online 29 June 2021
0360-1323/

Nomenclature

UHI	Urban Heat Island
TG	Thermal Gap
DTR	Diurnal Thermal Range
CS	Case Study
AR	Aspect Ratio
HW	Heat Wave
MRT	Mean Radiant Temperature
PET	Physiologically Equivalent Temperature
MOT	Maximum Outdoor Temperature
CT	Courtyard Temperature
OP	Occupancy Period

inhabitants [12]. This becomes an important consideration in different operational contexts [13], while buildings that offer the opportunity for greater adaptive capacity at different levels (i.e. at physical, behavioural or psychological) are more satisfactory for users [14].

Architecture and urban planning define the morphological properties of cities, but they also respond to aspects related to the daily life of citizens [15]. However, the relationship between the interior and exterior space of buildings has not been taken into account until now, so the focus on transitional spaces becomes important [16]. Courtyards play an important role in the traditional city texture in hot and warm climates, as an effective passive architectural design strategy [17]. The microclimate of courtyards is a subject of growing interest due to the need to design a more thermally resilient architecture. The tempering potential of these transition spaces [18] has been analysed in the scientific literature based on different parameters mainly related to their location, geometry and orientation [19]. In this context, designs with a more complex façade surface encourage the use of natural ventilation, since the different orientations and wind pressures improve cross ventilation [20,21]. With urban morphology generating spaces such as courtyards with temperate microclimates, the beneficial effect for the building is increased [22].

Research on the outdoor realm, on the other hand, has shown that people found outdoors in spaces such as urban squares, streets or parks, in their vast majority, are thermally comfortable [23], and contact with the outside environment enhances their adaptive capacity [24,25]. As a result, the positive and pleasant experience helps to expand the range of comfort conditions [26,27].

The courtyards, from vernacular architecture to the current times, are considered as part of the living spaces of the houses in the Mediterranean climate (Fig. 1). Their tempering potential has been known since ancient times, but only in the last decades, this has been quantified [28]. Courtyards have been used as effective buffer spaces, improving the harsher microclimate and encouraging greater use of outdoor space, in hot as well as cold climates (e.g. from hot arid [29], Mediterranean [30], tropical [31], to colder European climates [32]). Furthermore, research evaluating the effect of courtyards on thermal comfort has shown that the higher the external temperatures the better thermal regulators courtyards become, achieving a temperature difference with the outside of over 17 °C on very hot days in warm cities [30]. In addition, the porosity provided in the urban fabric by such morphology reduces the built-up area of the city, particularly important for city centres in warm climates [33]. As a result, courtyards become a considerable mitigation strategy against the UHI effect [34,35], due to the favourable microclimate generated inside [36]. Courtyards are also important for people's daily lives benefiting the environment of the adjacent rooms.

Within this wider context, the main focus of this study is not the courtyard as a passive resource to improve the indoor climate of the building, but rather evaluating the thermal comfort inside the courtyard itself as a semi-outdoor inhabited space. There are standards that allow the calculation of adaptive thermal comfort in indoor spaces (see Section 1.1) and several indices available to assess thermal comfort in outdoor spaces (see Section 1.2). However, no specific assessment tools are available for transitional or semi-outdoor spaces such as the courtyard.

Fig. 1. Traditional courtyard in a Mediterranean climate.

Borrowing analysis methods from both indoor and outdoor comfort theory, the focus of this work is two-fold. It aims to assess the suitability of the Mediterranean courtyard as a thermally comfortable space, evaluating thermal comfort and benchmarking against the international adaptive standards for indoor comfort EN 16978 and ASHRAE 55, as well as the PET index used specifically for the analysis of outdoor spaces. It also seeks to establish the suitability of these standards and indicators to accurately define the courtyard thermal comfort performance.

1.1. Adaptive thermal comfort standards. EN 16798 vs. ASHRAE 55

As the courtyards are treated as living spaces, this research attempts to investigate the comfort of these spaces, employing the adaptive thermal comfort standards for free-running buildings, i.e. for conditions without auxiliary heating or cooling. The two international standards for the indoor environment (EN 16798 [37] and ASHRAE 55 [38]) broadly employ the same general methodology but have different formulae for the assessment of the indoor environment of naturally ventilated buildings [39]. Both standards establish several categories for evaluating thermal comfort based on the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) indices, estimated according to the mean value of the thermal sensation votes (PMV) and percentage of thermally dissatisfied people (PPD).

For the calculation of comfort, both standards relate the indoor operative temperature to outside temperature values. EN 16798 relates to the Outdoor Running mean temperature on the day of analysis (θ_{rm}), and ASHRAE 55 to the prevailing monthly mean outdoor temperature ($T_{pma(out)}$). The main characteristics of both standards are presented in Table 1.

One of the main differences between the two standards is that ASHRAE 55 is based on a monthly mean calculation, while EN 16798 uses the running mean method, with bigger weighting on the conditions of the previous day. Another difference between the two standards is the external data used. While the EN 16798 standard does not indicate whether the meteorological data used should be those officially recorded, the ASHRAE 55 standard allows the monitored data to be recorded on-site or provided by public historical average data. This could imply a significant difference as official meteorological stations are located on the outskirts of the city, where the UHI effect is greatly reduced

Table 1
Main differences between EN 16798 and ASHRAE 55.

	EN 16798		ASHRAE 55
Category Limits	I – PPD <6%	I – PMV <+0.2	I – PPD <10%
	II – PPD <10%	II – PMV <+0.5	II – PPD <20%
	III – PPD <15%	III – PMV <+0.7	
	IV – PPD <25%	IV – PMV <+1.0	
Acceptability Limits	$f(x) = 0.33\ \theta_{rm} + 18.8$		$f(x) = 0.31T_{pma(out)} + 17.8 \pm T_{lim}$
Outdoor thermal values	$f(x) = (1 - \alpha)\theta_{ed\text{-}1}+\alpha\cdot\theta_{rm\text{-}1}$		$f(x) = \mathrm{mediaT}_{mda(out)}$ [7–30 days]
Metabolic rate	1–1.3 met		1–1.3 met
Clothing insulation	0.5–1.0 clo		0.5–1.0 clo
Application Range	Above 25 °C artificially increased air velocity can be used to compensate for temperatures		If T > 25 °C, then it shall be permitted to increase the upper acceptability temperature limits.

PPD Predicted Percentage of Dissatisfied
PMV Predicted Mean Vote
α Constant (Table 2 EN 16798 [37])
θ_{rm} Outdoor Running mean temperature on the day of analysis
$\theta_{ed\text{-}1}$ Daily mean outdoor temperature (previous day)
$T_{pma(out)}$ Prevailing monthly mean outdoor temperature
$T_{mda(out)}$ Mean daily outdoor air temperatures
T_{lim} Acceptability temperature limit
met Metabolic rate (units)
clo Clothing insulation (units)

compared to the urban environment.

1.2. PET as a comfort index in warm zones

In the last decades, comfort indices specifically for the external environment have been developed, taking into account the radiation fluxes [40]. The most extensively used is the Physiologically Equivalent Temperature (PET), developed by Matzarakis and Mayer [41]. It is a thermal index derived from the human energy balance, well suited for the evaluation of the thermal component of different climates. PET aims to assess the perception of thermal comfort conditions (from very cold to very hot, see Table 2) in various outdoor urban spaces [42]. Recent work, taking into account adaptation, has established different PET scales for different climatic zones [31], highlighting the thermal increase for the different sensations, as shown in Table 2.

1.3. Research focus

As has been highlighted, comfort studies have been focused predominantly indoors with increasing field surveys in outdoor environments [44,45]. However, very few investigations have addressed thermal comfort of transition or semi-outdoor spaces through field surveys, as opposed to modelling or simulation studies [46], and such work is limited in colder climates, such as Potvin's work on arcades [18].

In architecture, courtyards fulfil different roles, as already highlighted. As an outdoor space, they allow contact with nature, while as part of façade modulation they improve the natural ventilation potential of buildings. Moreover, in warm climates, transition spaces such as courtyards are liveable rooms, so their role must be taken into account in the design, particularly important under climate change.

According to previous research [47] courtyards are a resilient strategy for warm climates: the higher the outside temperature, the higher the courtyard tempering potential. Hence, the current study focuses on the thermal comfort conditions in courtyards under the harshest scenario, during summer and heat wave conditions. This research aims to reveal the importance of the courtyard as a living space in hot climates, so its results can influence urban design in other warm climate cities. Given the current absence of both: comfort standards and specific comfort indices for semi-outdoor spaces, this research aims to highlight the need for a precise comfort assessment instrument adapted to the characteristics of these spaces. This would avoid the disparity of results being affected by a non-specific reference framework, being applicable both to the evaluation of existing courtyards and their use as bioclimatic resources in building design.

Furthermore, this research analyses the performance of such spaces, making them comparable to both indoor and outdoor environments.

Considering the hybrid nature of the courtyard, in-between an indoor and outdoor space, to evaluate their thermal performance, the research borrows methods and indices from both indoor and outdoor comfort, the EN 16798 and ASHRAE 55 standards for indoor spaces, along with the PET index for outdoor spaces.

The study, based on field monitoring campaigns, aims to extend the potential use of these comfort indices to analyse thermal comfort in transition spaces. It aims to highlight the need for courtyards to be fully integrated into the design of buildings, stressing the need for building standards based on multi-nodal outdoor weather data to efficiently support climate-resilient urban design under climate change projections. The absence of regulatory standards for thermal comfort in semi-outdoor spaces has been the driving force to investigate the potential of extending the use of existing standards for assessing and establishing thermal comfort in these spaces.

2. Materials and methods

Two case studies of building courtyards located in Cordoba, a city characterized by high temperatures in summer, were analysed. Both courtyards were monitored in summer for two weeks, which also included heat wave conditions. The influence of bioclimatic strategies, such as shading devices, was also evaluated. The extensive monitoring undertaken enabled the analysis of the thermal comfort conditions in these spaces, using the methodologies currently employed for both indoor and outdoor conditions.

Table 2
Thermal sensation and PET ranges for different climates [43].

PET range for Western - Central Europe °C	PET range for Tel Aviv °C	PET range for Taiwan °C	Thermal sensation
4	8	14	Very cold
8	12	18	Cold
13	15	22	Slightly cool
18	19	26	Neutral
23	26	30	Slightly warm
29	28	34	Warm
35	34	38	Hot
41	40	42	Very hot

Table 3
Historical maximum and minimum and mean temperatures in Cordoba (°C).

Cordoba	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Max. Hist.	22,9	27,8	33	34	41,2	45	46,9	46,2	45,4	36	29,7	23,8
Min. Hist.	−8,2	−5	−4,2	0,2	2,4	7	11	11	6	1	−3,6	−7,8
Max. Mean	14,9	17,4	21,3	22,8	27,4	32,8	36,9	36,5	31,6	25,1	19,1	15,3
Min. Mean	3,6	4,9	7,4	9,3	12,6	16,5	19,0	19,4	16,9	13,0	7,8	5,5

2.1. Case study location and climate analysis

The case studies are located in the city of Cordoba in Spain (37° 53 '30 "N 4° 46′ 22″ W, elevation 106 m above sea level), reflecting the summer characteristic climatic conditions of the cities of southern Spain. The city belongs to a climate zone classified as B4, according to Spanish regulations (CTE) [48], which means a winter with a mild climate (B) and summers with extreme heat temperatures (4). At the same time, Cordoba is located in the Csa zone according to the Köppen climate classification [49]. This area is characterized by hot, dry summers with average maximum temperatures above 36 °C and mild winters with average temperatures of 11 °C. The historical maximum and minimum temperatures of Cordoba are presented in Table 3, obtained from the historical climatological database of the Spanish Meteorological Agency (AEMET) [50].

Previous studies carried out by the IPCC [51] report an increase in the average temperature of cities in the coming decades, and the city of Cordoba, with frequent heat waves in summer, is one of the most affected in Spain. According to forecast calculations of the regional government, according to scenario A2 of IPCC [52], the forecasts for the province of Cordoba until the end of the 21st century show an increase in average annual temperatures of 3.5 °C (Fig. 2).

To demonstrate the thermal improvement of the courtyard compared to the exterior, the analysis focuses on the diurnal temperature differences between the external environment and the courtyards. The Diurnal Thermal Range (DTR), the daily thermal difference between the maximum (T_{max}) and minimum (T_{min}) temperature value (Equation (1)) [53] is a useful indicator to evaluate local climate characteristics [54, 55]. For climate zone B4, the DTR in summer and during heat wave conditions is shown in Table 4.

$$DTR = T_{max} - T_{min} \tag{1}$$

The outdoor DTR on the day with the highest outside temperature is related to the courtyard DTR. This aspect describes the thermal variability produced in the courtyard compared to the exterior in a 24-h cycle [56–59]. DTR thermal variability has been previously analysed by other researchers that detected its important influence on people's health [60].

Table 4
Seasonal DTR range for the B4 Climate Zone [30].

SEASON	B4
Summer	**16–20 °C**
Summer (heat wave)	**> 20°C**

The selected case studies (CS1 and CS2) are two residential buildings with courtyards of different geometric characteristics. CS1 and CS2, located nearby and similar urban environment. They are representative of two different Aspect Ratio (AR) ranges, where AR relates to the height (H) and width (W) dimensions of the courtyard (Equation (2)):

$$AR = H/W \tag{2}$$

This equation enables the comparison of the comfort conditions in the courtyards on the base of their geometric characteristics. As AR is related to Sky View Factor (SVF) that represents the proportion of visible sky that can be seen from a specific point in the urban space, H and W of every courtyard have been measured at the cornice of the inner courtyard. AR (I and II) are defined, one for each of the two main dimensions of the courtyard plan. Nevertheless, other parameters, such as orientation and albedo are also used for this purpose [61]. Both courtyards present similar wall detailing and finishing materials. The courtyard inner walls consist of 40 cm traditional brick masonry with 2 cm cement mortar linings and a white paint finish with some yellowish ornaments in one of them. No insulation was considered given the historical typology of the building. The specifications of the wall are similar in both cases. The density of the traditional brick masonry is 2300 kg/m^3;

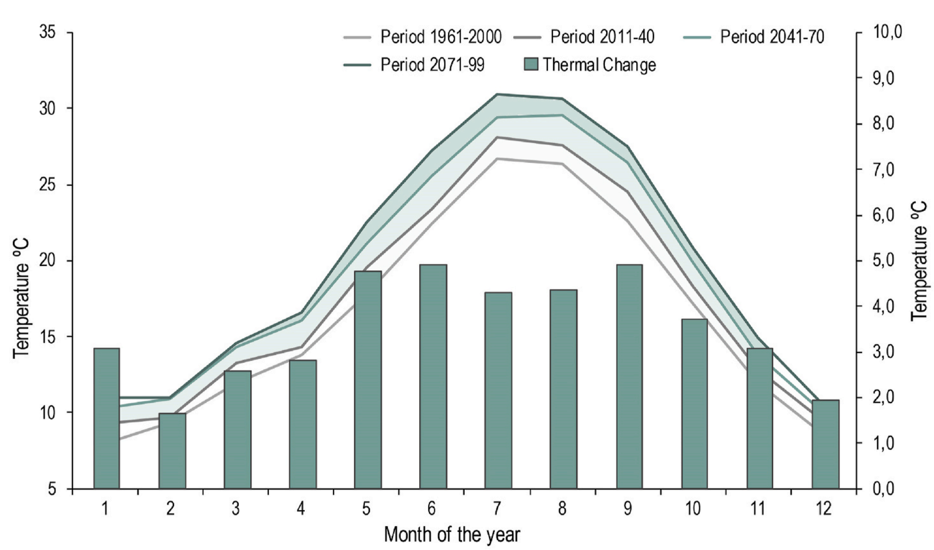

Fig. 2. Cordoba average annual temperature (°C) forecast up to 2070 according to scenario A2 of IPCC [51].

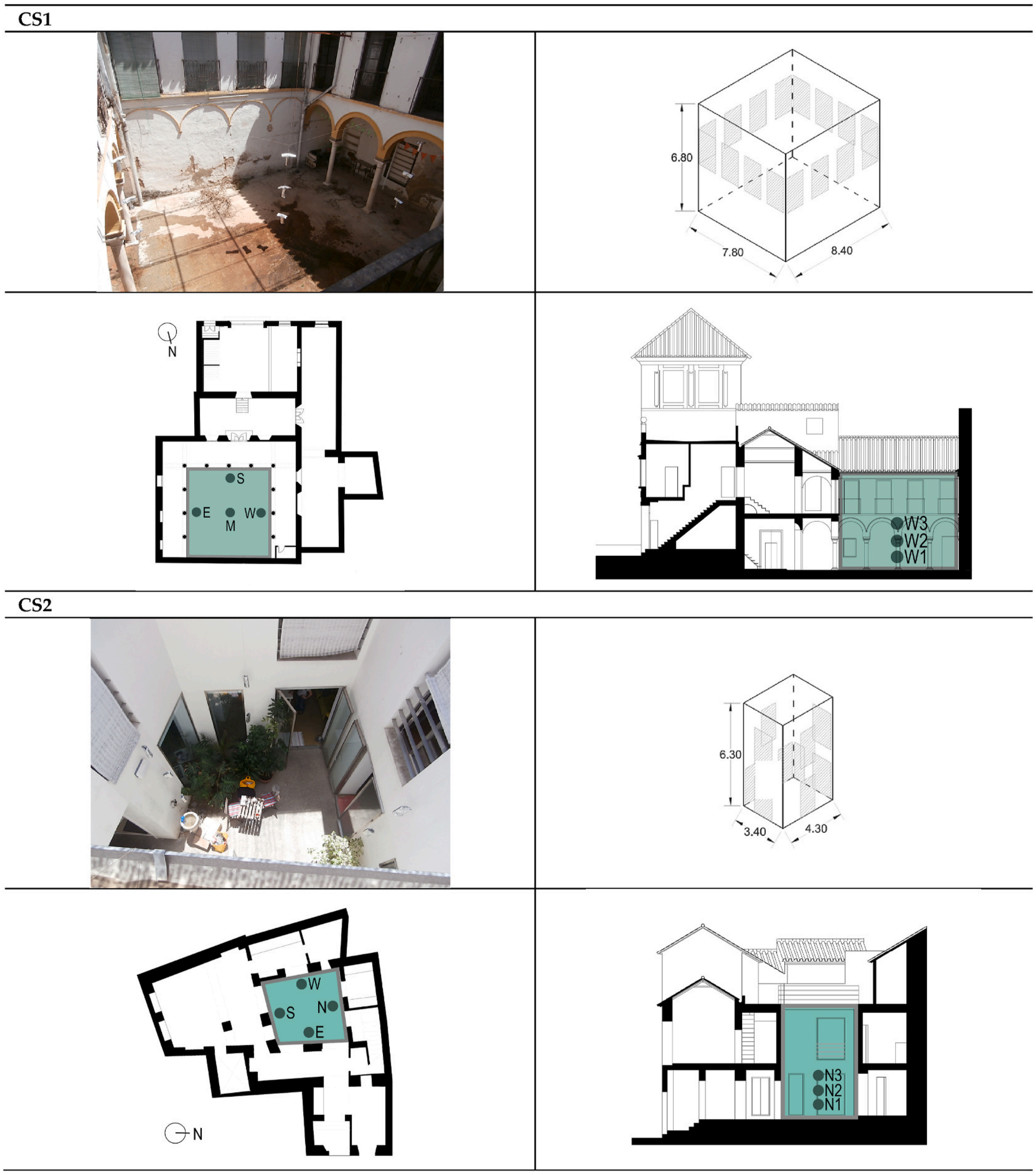

Fig. 3. Photographs, plans and sections of the different case studies.

Table 5
Location and geometric characteristics of the case studies analysed in Cordoba.

Case Study	Latitude	Longitude	Surface (m^2)	Dimensions (m)		Height (m)	AR I	AR II
CS1	37° 52′ 59″	4° 46′ 39″	65,5	8,4	7,8	6,8	0,81	0,87
CS2	37° 52′ 58″	4° 46′ 24″	14,6	4,3	3,4	6,3	1,47	1,85

cement mortar: 1600 kg/m^3. The envelope of both courtyards has a transmittance of U = 1,81 W/m^2 K. Fig. 3 shows image, dimensions, plan and section for each case study, detailing the position of the sensors identified with the façade orientation (N, S, E or W) and the height of the sensor (1, 2 or 3). W1 is the sensor located in the West façade at the first level (1.00 m), N2 at the second level (2.00 m) of the North façade and so on. Moreover, Table 5 shows the general characteristics of each case study.

2.2. Field monitoring campaigns

The field monitoring campaigns in the two case studies were conducted for the same two-week period, following the protocols established by previous studies [62]. Both buildings were monitored during an unoccupied period to avoid occupant interferences so all the windows were always closed. Data collection was carried out during the summer season when the outdoor temperatures are highest, which is the critical period. Staying outdoors is difficult due to extreme temperatures, exceeding 40 °C in the middle of the day, and above 30 °C until midnight. To evaluate the effect of these spaces, two different campaigns were organised, representing two different thermal ranges; for a week with typical summer temperatures, and a week for the worst-case scenario [63]. The latter refers to a heat wave (HW), which according to AEMET [50] for the province of Cordoba, includes outdoor temperatures above 41.2 °C for at least three consecutive days.

A portable meteorological station with a measuring interval of 15 min, model PCE-FWS, was located on top of the roof of the building, in an area of direct exposure to the outside. In addition, 12 data loggers (three for each façade of the courtyard) with the same measuring interval TESTO 174 H (dry bulb temperature and relative humidity) and TESTO 174 T (dry bulb temperature) were placed inside the courtyards, although only those placed on the north-facing façade, receiving the least direct radiation to avoid overheating of the sensors were used. Sensors were placed at different heights, to account for the thermal stratification of these spaces, at +1.00 m, +2.00 m and +3.00 m, referring to the height inhabited by users. Data were also recorded at all the orientations of the courtyard at the same levels, due to the nominal height for users and sedentary activities. To demonstrate the effect of the UHI effect, Fig. 4 reflects the temperature difference monitored for three typical summer days comparing data provided by AEMET [50] located in a rural area and by a local portable weather station placed in an urban environment. In addition, the mean radiant temperature (MRT), necessary to calculate the operative temperature required for thermal comfort analysis has been calculated using QUESTemp 34/36 to record wet-bulb globe temperature in the middle of the courtyard. Technical data of measurement instruments are shown in Table 6.

Table 6
Technical data of the measurement instruments.

Environment	Sensor	Variable	Accuracy	Range	Resolution
Courtyard	TESTO 174H/T	Dry bulb Temp.	±0.5 °C	−20 to +70 °C	0.1 °C
		RH	±0.1%	0–100%	2%
	QUESTemp 34/36	Dry bulb Temp.	±0.5 °C	0 to +120 °C	–
		RH	±0.5 °C	20–95%	–
Outdoor	PCE-FWS 20	Dry bulb Temp.	±1 °C	−40 to +65 °C	0.1 °C
		RH	±5%	12–99%	1%
		Wind	±1 m/s	0–180 km/h	–

3. Results

3.1. Tempering potential of courtyards

The data obtained during the monitoring campaigns are represented in Fig. 5 with data recorded in 15-min intervals, therefore the irregularity of the data series. These relate to outdoor temperatures in the monitored period and temperature inside the courtyard, where the improved conditions become noticeable.

The thermal reliance of the courtyard on the outdoor climate implies that even in case studies such as CS1 with AR<1 (Fig. 5), their efficiency as passive cooling systems increases as outdoor temperatures become higher.

In each case, the analysis presents the DTR for the external environment compared to the two courtyards for five days for a typical summer week (Fig. 6a) and for the heat-wave (Fig. 6b).

The results have focused on the thermal gap (TG) generated by the courtyard microclimate, i.e. the temperature difference between maximum outdoor temperature (MOT) and courtyard temperature (CT), defined by the following Equation (3).

$$TG = MOT - CT \tag{3}$$

TG values in both cases studies are between 2.5 °C and 8.4 °C when the maximum outdoor temperature is around 37 °C (summer), with values increasing between 9.8 °C and 13.9 °C when the maximum outdoor temperature exceeds 44 °C (heat wave). Furthermore, the difference between the outdoor and courtyard DTR presents similar results to [56–58], with a thermal range of 6.1 °C–12.3 °C. Furthermore, the thermal behaviour of the courtyard becomes particularly favourable when the outside temperature increases.

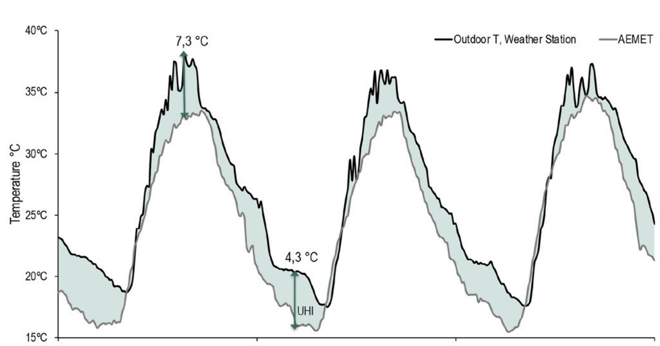

Fig. 4. Thermal difference between published (AEMET [50]) and measured values due to the UHI effect.

3.2. Adaptive thermal comfort in courtyards according to EN 16798

Adaptive comfort is studied in the two case studies according to the model described by EN 16798. The necessary data for its representation and subsequent analysis are Operative Temperature (θ_0) (Equation (4)) and Outdoor Running mean temperature (θ_{rm}) (Equation (5)).

$$\theta_0 = (CT + MRT) / 2 \tag{4}$$

where CT is courtyard temperature and MRT is mean radiant temperature.

$$\theta_{rm} = (1 - \alpha)\, \theta_{ed\text{-}1} + \alpha \cdot \theta_{rm\text{-}1} \tag{5}$$

where α is a constant value and $\theta_{ed\text{-}1}$ is the average daily outside temperature of the previous day (24 h).

When the data have been calculated, it can be verified if the temperatures inside the courtyards studied are within the limits established by EN 16798. Considering that the case studies are a transition space, the graph limits in the standard have been extended using the relevant equations for each category. These equations were used to establish the limits of the operative temperature. Fig. 7 shows the courtyard temperature within the different comfort ranges (Cat I, II and III) for the 24-h daily period during the representative 5-day period.

In terms of adaptive thermal comfort, both courtyards' performances converge by increasing the outdoor thermal range during a heat wave (Fig. 7). In contrast, during summer, the different ARs mean that CS2 is almost entirely under the comfort range (for Cat III) versus CS1 which goes out of comfort range during the hottest hours of the day.

3.3. Adaptive thermal comfort in courtyards according to ASHRAE 55

In the adaptive comfort study according to ASHRAE 55, the arithmetic average means an outdoor temperature value for 7–30 days is taken into account for the calculation of prevailing mean outdoor temperature. In the case of operative temperature, Equation (4) is employed. In this case, the values of the previous two weeks have been taken into account, with a prevailing outdoor temperature of 28.1 °C for the typical summer, and 29.4 °C for the heat wave period respectively. Fig. 8 shows the courtyard temperature within the different comfort ranges for the 80% and 90% acceptability limits for the typical and heat wave period as before.

In the case of considering ASHRAE 55 standard as a reference, the overall adaptive thermal comfort assessment of both case studies is similar to EN 16798 (Fig. 8). However, the courtyards' comfort under ASHRAE 55 results in worse performance, especially during a heat wave.

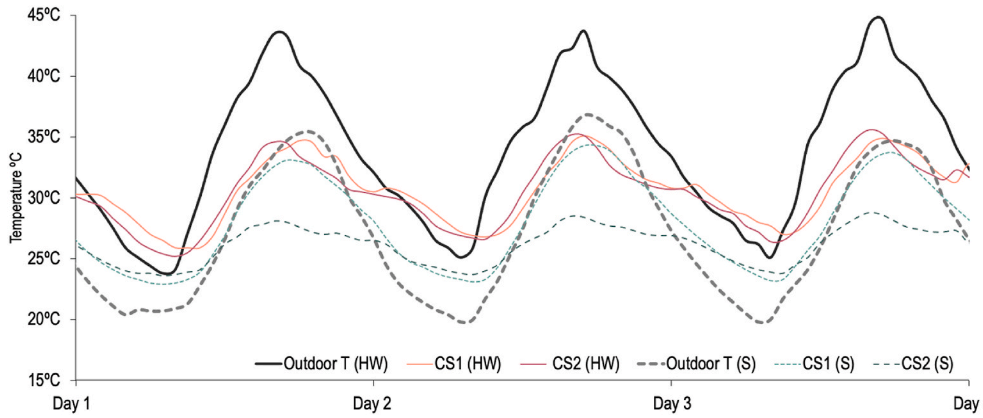

Fig. 5. Monitoring campaigns. Outdoor temperature vs Courtyard temperature.

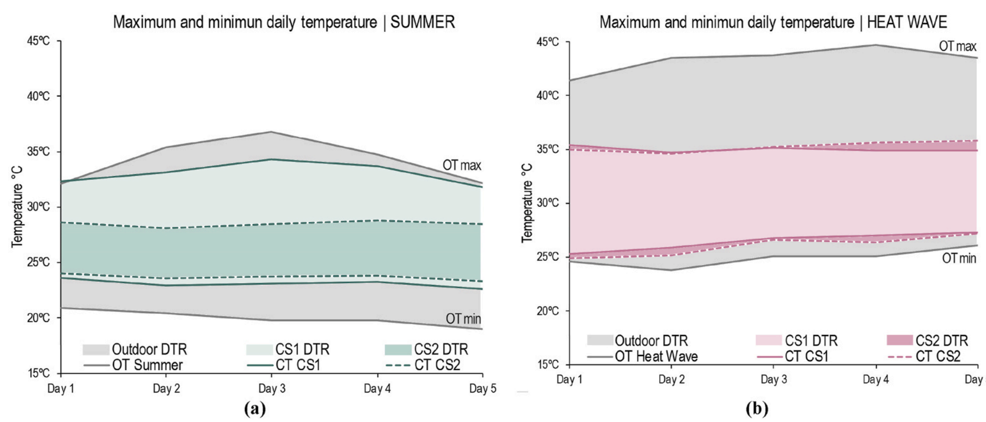

Fig. 6. Maximum and minimum monitored daily temperature. (**a**) typical summer and (**b**) heat wave period. Nomenclature: Outside Temperature (OT), Courtyard Temperature (CT), Diurnal Thermal Range (DTR).

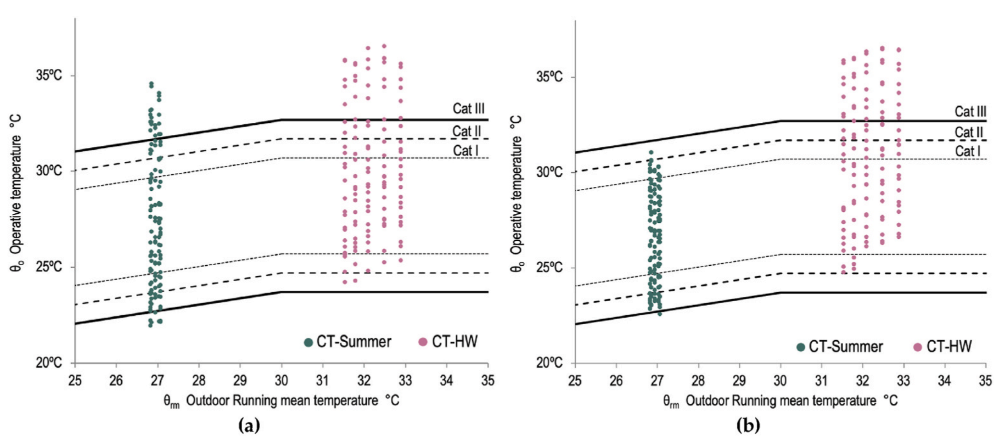

Fig. 7. Adaptive thermal comfort range in courtyards according to EN 16798 (**a**) CS1 and (**b**) CS2.

3.4. Adaptive thermal comfort in courtyards with shade elements

The implementation of passive strategies is important to improve the thermal comfort of courtyards and adjacent rooms [64,65]. To address this, a third monitoring campaign was conducted in CS2 to determine the influence of a shading element during a heat wave on the courtyards. A shading element was placed at building roof height, 6.30 m above the courtyard floor. The shading element was fixed to the railings (Fig. 9a) so as not to obstruct ventilation inside the courtyard. It was placed during the heat wave period (Fig. 9b) of the second campaign, with the sensors at the exact same position, and similar weather conditions (Fig. 9c).

The porous texture fabric used in the experiment was a black, high-density polyethylene material (UV filter 75% and about 70 g/m^2 density) to allow wind flow out of the courtyard.

The results of the monitoring campaign showed a TG of 15.4 °C, which represents a difference of 1.5 °C compared to data recorded without the shade. However, when analysing the behaviour of the courtyard in terms of DTR, there is a difference of 17.4 °C, which represents a significant improvement in the behaviour of the courtyard in a

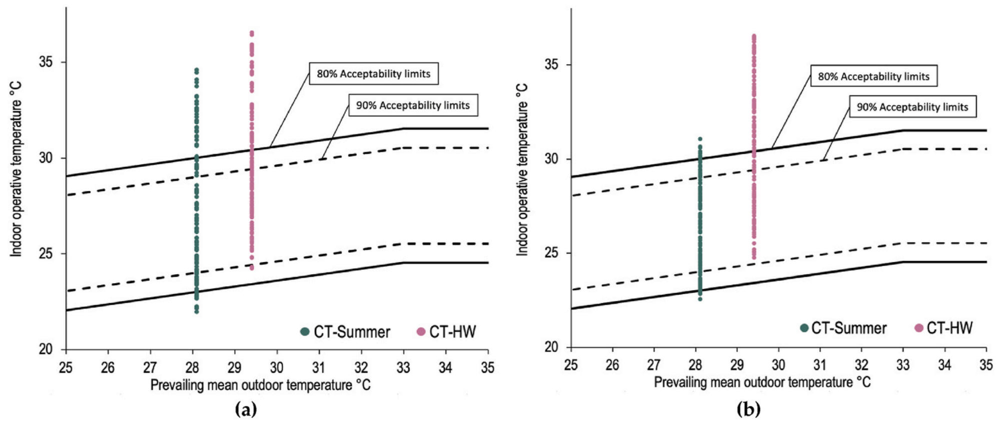

Fig. 8. Adaptive thermal comfort range in courtyards according to ASHRAE 55 (a) CS1 and (b) CS2.

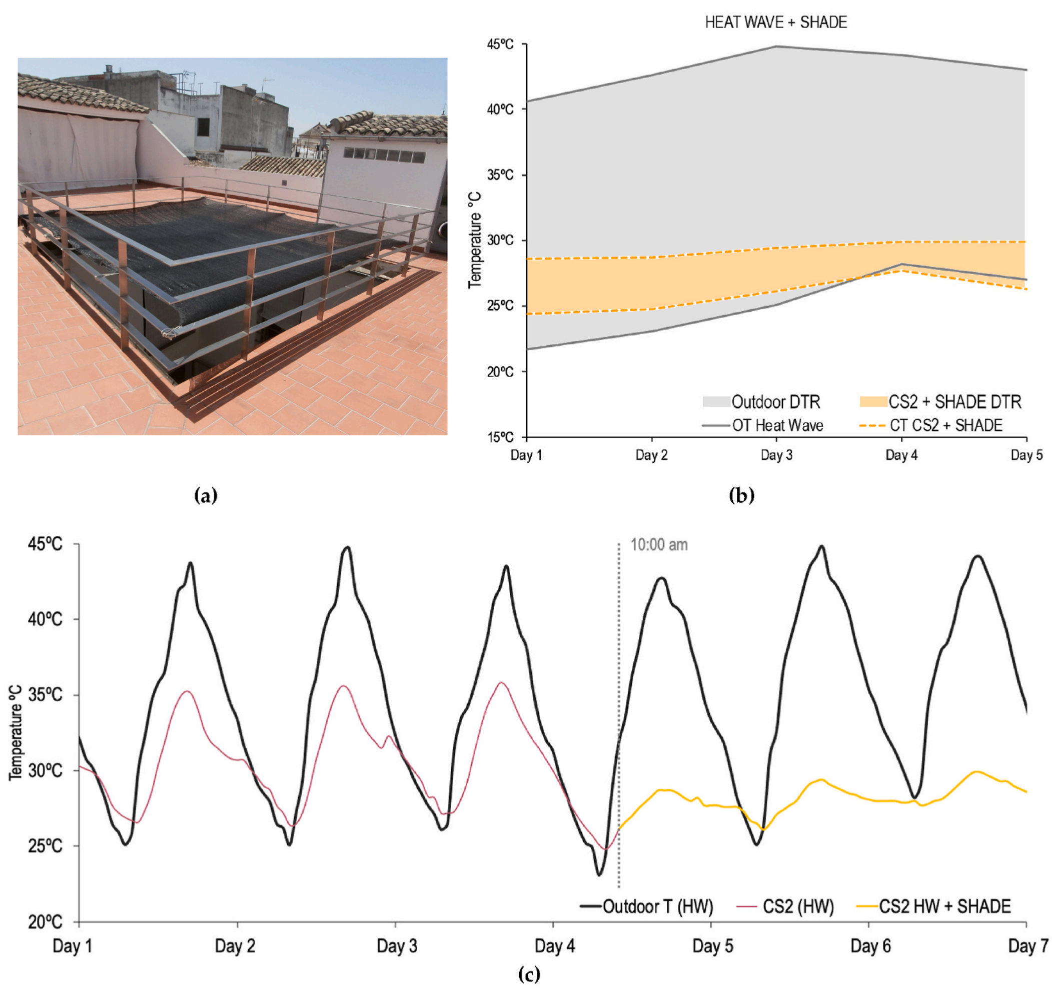

Fig. 9. a) Placement of a shade element as passive strategy in CS2. b) Maximum-minimum monitored daily temperature with shade. c) Results of the monitoring campaign pre/post installation of the shading element. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

24-h cycle. Fig. 10 shows the comfort results according to EN 16798 and ASHRAE 55. Most of the hours of the day the courtyard is within the limit categories established by the EN 16798 standard (Fig. 10a). In the case of ASHRAE 55, the results in Fig. 10b, again show a noticeable improvement when the shading is implemented.

3.5. Comfort analysis using PET

The PET comfort index is calculated for the different monitoring periods for both case studies, using Rayman free software [66] and the results are shown in Fig. 11.

CS2 demonstrates a lower PET index reflecting a better thermal behaviour in both typical and heatwave periods. Previous studies in the

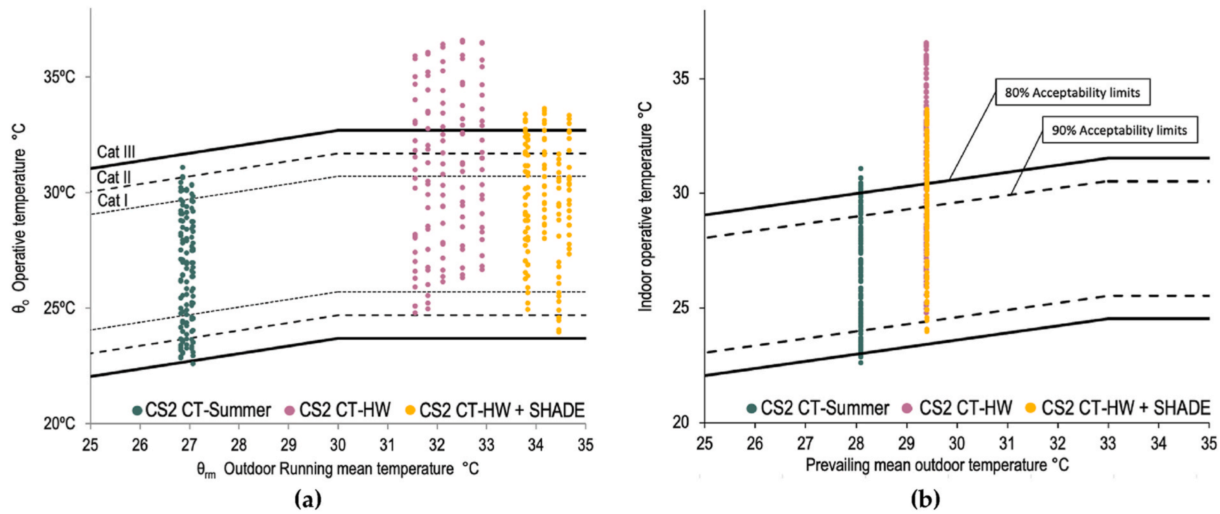

Fig. 10. Improvement of the thermal comfort conditions with added shade elements in CS2 according to (**a**) EN 16798 and (**b**) ASHRAE 55. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

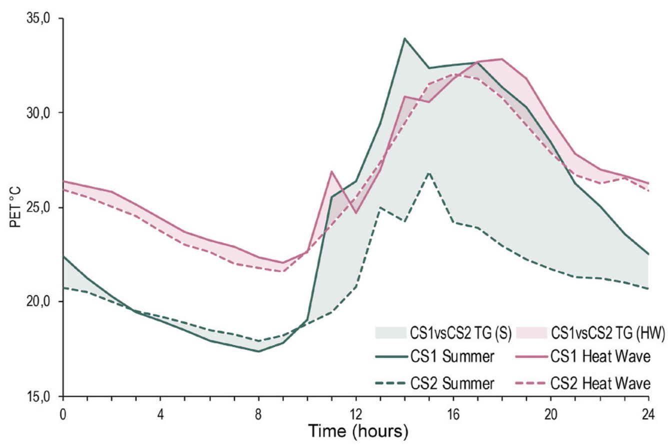

Fig. 11. Adaptive thermal comfort in courtyards according to PET index.

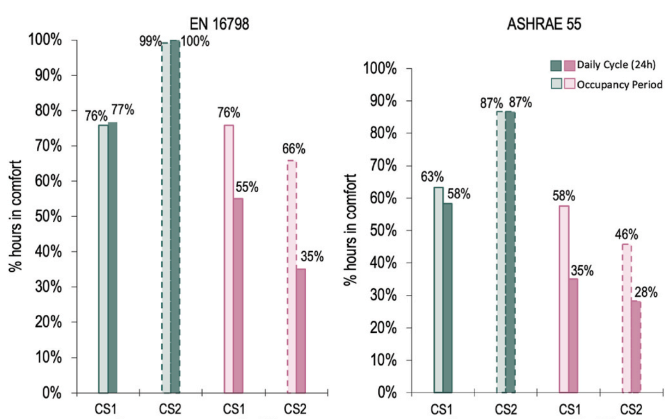

Fig. 12. Percentage of comfort hours in courtyards according to EN 16798 and ASHRAE 55, for the 24-hr period and the 12-hr period of effective use.

Mediterranean climate [43] defined the 'neutral' PET range of thermal sensation between 19 and 26 °C. While courtyard CS2 only overheats in the midday-early evening period of the day during the heatwave, CS1 shows similar overheating during both typical and heatwave conditions, due to the larger exposure to the solar radiation.

4. Discussion

4.1. EN 16798 vs ASHRAE 55

The statistical analysis of the comfort range presented earlier shows that the temperature inside the courtyards is within the limits established by the EN 16798 most of the time (Fig. 12).

Analysing the complete 24-h daily cycle, courtyards have an average comfort percentage between 77 and 100% according to EN 16798, and between 58 and 87% according to ASHRAE 55 if a typical summer day is considered. In heat wave periods, these intervals shift towards 35–55%, according to EN 16798, and 28–35%, according to ASHRAE, which highlights the tempering potential of these spaces, as well as their usefulness as a comfortable space during most of the daylight hours in the warmest part of the year.

Courtyards are conceived in the Mediterranean culture as semi-exterior rooms of the house. They are effective living spaces with flexible specifications. For this reason, a period of regular occupation of these spaces has been selected, establishing a daily occupation schedule for the summer. The estimated range of occupation is from 9.00 to 15.00 h, and from 17.00 to 23.00 h, taking into account the daily rest period after lunch in the Mediterranean culture (siesta time). For this reason, the comfortable conditions are also calculated for the potentially occupied period shown in a lighter colour (Fig. 12).

On this assumption, examining the thermal comfort conditions of these outdoor "living rooms" for the period they are occupied, average comfort in the analysed case studies remains for 88% for the typical summer, decreasing significantly to 45% for the heatwave period according to EN 16798.

Due to the calculation method of the American standard, the values of prevailing mean outdoor temperature are the same for the entire period analysed for each courtyard. The results show better performance in CS2 than in CS1.

The results show an adequate behaviour of the courtyards in terms of comfort. For all cases considered, the average number of hours per day within comfort is high, being comfortable the whole daily cycle in some of them.

Considering a typical week during the summer season, for both EN 16798 and ASHRAE 55, and for both case studies, the comfort period inside the courtyard is quite similar, whether a 24-h cycle or the actual occupancy hours are considered.

Conversely, in the case of a heat wave, for both standards and both case studies, there is an improvement in the comfort percentage when

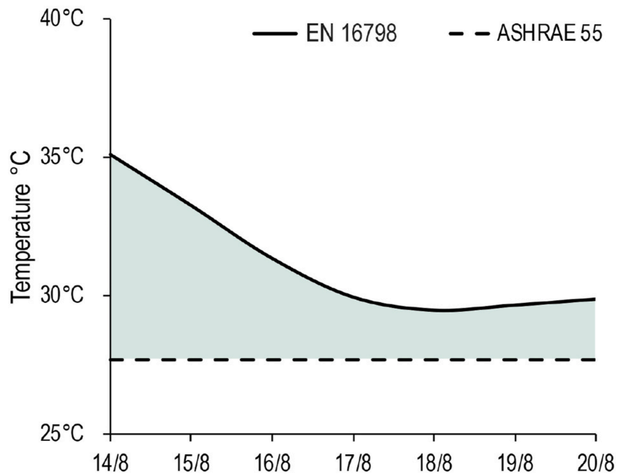

Fig. 13. External thermal values according to EN 16798 and ASHRAE 55.

considering the actual occupancy hours versus the 24-h cycle. In the case of the EN standard, this enhancement in comfort hours implies a variation from 55% to 76% for CS1, and from 35% to 66% for CS2.

However, significant differences could be observed during the heat wave period depending on the standard applied. The percentage of comfort hours for CS1 considering ASHRAE 55 is 58%, and 76% if EN is used. While for CS2, comfort rates vary from 46%, considering ASHRAE 55, to 66%, employing EN 16798. This is due to the different outdoor temperature values used in both standards, as shown in Fig. 13.

As a result, EN 16798 reflects better the thermal variability occurring in hot climates, ASHRAE 55 has a steady outdoor temperature value every day analysed, while EN 16798 considers outdoor temperature values based on the previous day.

4.2. Implementation of passive strategies. Shade elements

The implementation of passive strategies through the integration of an awning during the heatwave (yellow colour), allowed the courtyard to be at a comfortable temperature for a longer period. The percentage of comfort hours increased from 85% to 89% when considering only the time of real occupation period (12 h) according to EN 16798, which provides a comfortable space for most of the day (Fig. 14). If using ASHRAE 55, the percentage of comfort hours is considerably smaller in both occupancy times, increasing from 42% to 59% for the occupied period (Fig. 14). It is relevant to note the different sensitivity between the two standards, that in this case, under the same circumstances, EN 16798 standard doubles in the case of the 24-h cycle the percentage of comfort hours compared to ASHRAE 55.

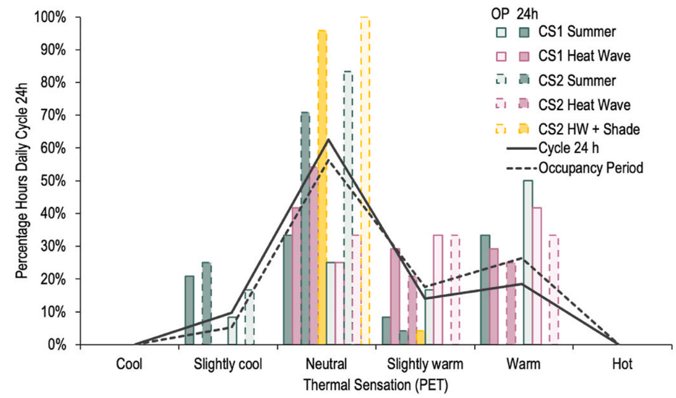

Fig. 15. Percentage of comfort hours in courtyards according to PET.

4.3. PET

The analysis from PET have been plotted in Fig. 15 as a function of the thermal sensation established for the climate most similar to that of the location of the case studies, i.e. the city of Cordoba [43]. As in the previous cases, the percentage of hours of the day in which the courtyard is in each thermal range of PET and simultaneously the period of actual occupation of the courtyard are represented.

If acceptable thermal sensation is considered between the values included by Slightly Cool, Neutral and Slightly Warm, calculated PET shows that the CS1 is in thermal comfort for 60% of the daylight hours with typical summer temperatures, and 70% in the heatwave. The CS2 courtyard, with the best tempering potential, is 100% of the hours in thermal comfort during the typical summer, and 75% during the heatwave. The effect caused by the added shading element was beneficial, increasing comfort to almost 100% of the hours, predominantly in neutral thermal sensation.

Analysing the potential occupation period, CS1 shows 50% of the time with the courtyard in comfort temperature in the typical summer and 59% in the heatwave. Similarly, CS2 shows better tempering

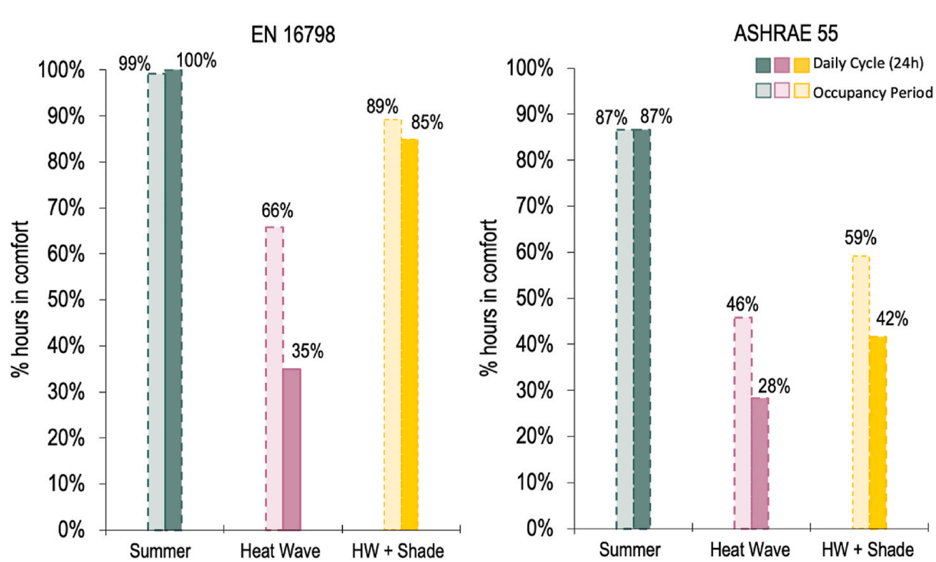

Fig. 14. Percentage of comfort hours when monitoring CS2 with shading elements according to EN 16798 and ASHRAE 55.

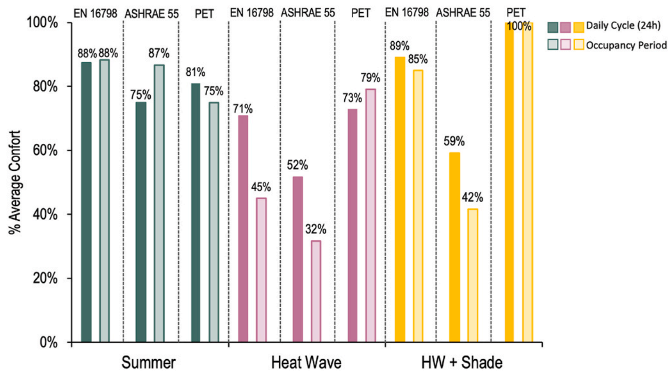

Fig. 16. Percentage of comfort hours EN 16798 vs ASHRAE 55.

potential with 100% of the hours in thermal comfort in the summer and 67% in the heatwave.

4.4. Impact of the calculation model

Using different limit categories for comfort, as well as methodologies that take into account different periods and calculations of outdoor temperature, produces different results in both standards. Fig. 16 shows a comparison of the thermal comfort results in courtyards according to EN 16798 and ASHRAE 55, for the 24-h period along with the actual courtyard Occupation Period (OP). In addition, both standards, with comfort indices for indoor spaces, are compared with the index for outdoor environments PET.

The results demonstrate great differences, the most noticeable in the implementation of shading. There is a difference of more than 43% of the hours of comfort in the period of actual occupation between both standards. Despite having a more restrictive index of dissatisfaction PPD EN 16798 (PPD <15%) in the limit category, compared to PPD <20% of ASHRAE 55, the adaptive comfort calculation using EN 16798 results in courtyards having a higher percentage of hours within comfort for all the cases. Using outdoor temperature data from the previous day allows a more accurate reflection of the tempering potential of the courtyard.

If the comparison is performed between indoor and outdoor indexes, ASRAE 55 and EN 16798 versus PET, results show a higher percentage of comfort hours according to PET. For this purpose, the thermal sensation range that has been considered cover the values of the three core categories: slightly warm, neutral and slightly cool as indicated by previous research [43].

Results show a homogenisation between both measurement periods (24 h and OP) in the PET index with respect to both indoor indices. These results are quite different for indoor indices when outdoor temperatures are higher during a heat wave. Overall, EN 16798 results are closer to PET index results, which means that this standard is more suitable for assessing comfort in this type of semi-outdoor spaces in this climate.

5. Conclusions

Courtyards act as important buffer spaces, but are not accounted for in comfort standards. In fact, the main focus of the standards in terms of energy-saving and comfort in Spain [66] is the reduction of heat losses. In recent years, cases of documented overheating in new buildings, even in temperate climates, such as in the United Kingdom, suggest the need for a greater emphasis on cooling strategies and update of regulations [67][68].

The normative standards that regulate adaptive comfort do not take into account parameters that integrate this type of space in buildings, with the tempering potential that the generated microclimate provides. TG values in the case studies analysed reach 8.4 °C in the period of typical summer temperatures, increasing to 13.9 °C cooler than the outside in the heat wave period. The courtyard as a habitable room is a daily premise in Mediterranean culture, and the potential of calculating thermal comfort in these spaces acknowledges this. The two standards that take into account adaptive comfort for indoors require similar established parameters, but with a different methodological development for transitional spaces outdoors, that recognize differences in the sensation of thermal comfort. The values obtained in the two case studies analysed, in the warm season, 77–100% of the day the courtyards are in comfort according to EN 16798, compared to 58–87% according to ASHRAE 55. If only the occupancy period of the courtyard is analysed, 76–99% of the hours in the warm season are comfortable according to EN 16798, compared to 63–87% according to ASHRAE 55.

The main objective of this research was to demonstrate the effectiveness of courtyards as thermally comfortable spaces based on outdoor climatic parameters during a heat wave using the two main adaptive comfort standards EN 16798 and ASHRAE 55, and an outdoor comfort index, PET. Therefore, the research did not take into account the influence of the interior of the building on the courtyard, as well as possible infiltrations and exfiltrations. Results show that 71% of the day in heat wave periods, the courtyards are at comfort levels according to EN16798, which reduces to 52% according to ASHRAE 55. When only the occupancy period is considered, up to 45% of the occupied hours of the courtyards during a heat wave are in comfort according to EN16798, compared to 32% according to ASHRAE 55.

The influence of shading strategies has also been analysed, highlighting their importance, where up to 89% and 59% of the hours of the day in heat wave periods are in comfort according to EN16798 and ASHRAE 55 respectively. This slightly reduces to 85% and 42% of the occupied hours being in comfort according to EN16798 and ASHRAE 55 respectively.

Using the PET index, the results show comparable percentage of comfort hours in the courtyard, 81% in typical summer, which increases to 73% during a heat wave and up to 100% with the implementation of a shading.

Extending the applicability of indoor comfort standards for free-running buildings, the work further highlighted that the EN16798 standard provides similar comfort prediction rates with PET in the climate of southern Spain, particularly for typical outdoor summer temperatures. This would suggest that future research could focus on determining appropriate comfort indices for semi-outdoor or transition spaces that can eventually be fully embedded in local building codes and regulations.

More importantly, the work demonstrated that courtyards are a valuable resource providing a tempering strategy in a city [67], providing a kind of semi-outdoor living room with a real ability to provide thermal comfort for users. This research can be further enhanced by extending the analysis to the full cycle of a year to determine the comfort of courtyards in cold season. In addition, it can be considered as an economic and sustainable passive strategy capable to improve and extend adequate levels of thermal comfort for most of the day even during extreme outdoor temperature periods. Given our warming climate, such design strategies provide effective mitigating for cities.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the National Government of Spain FEDER/Ministerio de Ciencia e Innovación-Agencia Estatal de Investigación RTI2018-093521-B-C33. The authors gratefully acknowledge

AEMET (State Meteorological Agency) for the data supplied and the financial support of the Ministerio de Ciencia, Innovación y Universidades, via one pre-doctoral contracts granted to Diz-Mellado (FPU 18/04783) and López-Cabeza (FPU 17/05036).

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