Thermal performance of historic buildings in Mexico: an analysis of passive systems under the influence of climate change

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Abstract

The commitment to energy efficiency in buildings has become more relevant as a measure to mitigate the increase in temperature established by the Paris Climate Conference. This phenomenon has increased in historic buildings, which are not designed to maintain an acceptable level of thermal comfort for the occupants despite the recent increase in temperature, resulting in intensive energy use. This research evaluates the thermal performance of a passive cooling system in a historic religious building through a correlational method. The analysis included different occupancy levels and the climate model provided by the Intergovernmental Panel on Climate Change. The study considered meteorological data from the current scenario (2022) and two chronological progressions throughout the 21st century (2050, 2100). The meteorological database of future projections was collected by the Meteonorm software considering three climate change scenarios, specifically the Representative Concentration Pathways (RCP). The objective was to determine the effectiveness of the passive cooling system in mitigating climate change. The findings showed a reduction in radiative and conduction heat gains of 70% in the current scenario and a decrease in temperature for the most unfavourable scenario (RCP 8.5 in 2100) between 1.4 °C and 1.9 °C. These results demonstrate the effectiveness of using efficient passive systems to mitigate climate change in temperate climates.

Keywords: Climate change, historic building, Sustainable energy technologies, preservation risks, passive cooling system.

Nomenclature	
RCP	Representative Concentration Pathways
NZEB	Net-zero energy or net-zero emission buildings
PCS	Passive Cooling System
PMARE	Percentage of mean relative absolute error
RMSE	Mean square error
CDH	Cooling degree hours
Tcomf	Comfort temperature
Tout	Outdoor temperature
T_{in}	Indoor temperature
ρ	Density
Ce	Specific heat
λ	Thermal conductivity
U	Thermal transmittance
O	Observed data
P	Projected data
Q_{tot}	Total heat gain
Qc	Conduction heat gain
CS	Shading coefficient

FG	Solar gain factor
Qr	Radiation heat gain

1. Introduction and background

Since 1896, there has been an abrupt increase in temperature, documented by institutions and scientists, increasing the concept of climate change [1], a phenomenon that directly affects natural ecosystems and built environments. Through international agreements, the most optimistic scenario states that the temperature could rise by up to 1.5 °C by 2035 due to the increased inertia of the atmospheric system [2]. Beyond 2035, significant variations in the future climate will be expected to depend on greenhouse gas concentrations. The Intergovernmental Panel on Climate Change describes this phenomenon in numeral reports of predictive models by the Representative Concentration Pathways (RCP) with a high level of confidence in the quantitative information [3]. Robust theory calls for immediate action to address climate change to achieve positive and-lasting effects on the climate [4]. Studies of the past 20 years have shown that urban vegetation directly impacts the regional climate, mainly temperature [5]. However, Duffy et al. [6] predicted that within 20 to 30 years, plants would stop sequestering less than 25% of the carbon emissions they usually sequester today, accelerating the effects of climate change. Through respiration, plants expel a percentage of the carbon dioxide emissions absorbed during photosynthesis. When reaching a limit point in any ecosystem, the vegetation ceases to be a carbon sink to a carbon source; that is, it exhales more gases than it inhale [7]. Causing phenomena such as the urban heat island, and establishes patterns of climate change that influence the built environment and the users' thermal comfort. Since the increase in temperature and related phenomena such as heat waves, urban heat island or heat stress, scientific interest in mitigation strategies, adaptation, and indicators has increased to evaluate the effectiveness of interventions aimed at reducing the effects caused by excess carbon in the environment in different scenarios [6,8–11].

It is essential to change construction paradigms, consider climate conditions and increase the certainty levels offered by applying technological innovations aimed at "decarbonisation" to mitigate environmental problems and future resource demands. The climate aim of decarbonisation implies a reduction of temperature in warm seasons with a residual use of active systems to achieve user comfort. Simultaneously, the social objective focuses on avoiding future damage associated with climate uncertainty, and the forward-looking objective seeks a stable capacity of the atmosphere to store greenhouse gases despite depletion [12].

The Paris Agreement (COP21) [13] established a framework to avoid an increase in global warming below 2 °C, to limit it to 1.5 °C. The Agreement searches to enhance and strengthen the capacities of countries to mitigate and cope with the effects of climate change. The building sector is responsible for 35% of final energy consumption, and 38% of CO_2 emissions [14], and that 55% of the world's people currently live in cities, with a projected increase of 13% (adding up to 68%), and population growth of about 2.5 billion additional people living in urban areas by 2050 [15], it is expected to double the amount of built-up area, especially in developing countries, by 2050. Given the above, a doubling of built-up area, especially in developing countries, is expected by 2050 [14]. Therefore, solutions such as those offered by net-zero energy or net-zero emission buildings (NZEB) represent an area of global opportunity, especially in developing countries. Regarding these solutions, researchers such as Droutsa et al. [16] analysed non-residential buildings and found that only 4% meet thermal requirements in the building envelope to reduce emissions. Meanwhile, Ouali et al. [17] proposed a control algorithm to reduce energy consumption in office buildings.

In the recent years, there has been an increase in energy demand, reaching 20 000 TWh in pollutant emissions of 38 million tonnes of CO_2 [18]. The latest studies show that, of the worldwide energy demand, buildings consume around 30% of the total energy and contribute to 28% of global energy-related CO_2 emissions [19]. The building’s operation stage is important in terms of energy use and greenhouse gas influence, which generally contribute between 60% and 90% of the total environmental impact of buildings [20]. Energy demand is directly linked to climate conditions, so global warming specifies a direct impact on energy requirements, specifically on the cooling and heating needs of buildings [21]. This process is even higher in historic buildings because many of them were self-built, i.e., without proper professional advice in the planning of architectural design integrated with energy efficiency strategies; above all, without thinking about the life-cycle effects of materials and their future environmental repercussions. Consolidating energy efficiency in all climates would provide both environmental and economic benefits in all sectors. Yüksel et al. [22] found that ventilation solutions in temples generally do not meet comfort or health needs. Therefore, to reduce pollutant emissions in historic buildings in developing countries, it is necessary to reduce the operational mismatch for which they were not originally designed.

In Mexico, national energy consumption increased 74.1% in the last 25 years, while energy sector consumption increased 12.1%, and total final energy consumption grew 47.5% in the same period [23]. Cooling tasks accounted for 21% of the electricity consumption. Among end uses, energy consumption for space cooling is highest in extremely warm and tropical regions. However, temperate climates account for 4.7% of electricity consumption on average per year [24]. It is necessary to consider energy efficiency, environmental care, and the repercussions of climate change on the thermal performance and construction systems in historic buildings to guarantee the users' comfort in self-built buildings and to determine their capacity to tolerate the climate change.

Historical buildings have been studied from the perspective of the climate change impact on the protection and conservation of historical heritage on thermal and energy performance [25]. Xiao et al. [26] evaluated the adaptation for different historic structures and found that maintenance is crucial for preserving historic buildings and their occupancy levels. Li et al. [27] sought to decrease the uncertainty of climate change for historic buildings with a climate adaptation plan with a historical-economic optimisation approach and found an opportunity to integrate an adaptive perspective.

Prieto et al. [28] studied future scenarios between climate change and historic buildings to determine preventive actions. Coelho et al. [29] developed simulations in different climates, Moreno et al. [30] implemented an evaluation model for the preventive conservation of heritage buildings, and Bienvenido-Huertas et al. [31] analysed the environmental performance inside a historic building in a warm climate. From an energy performance perspective, Caro et al. [32] analysed hybrid systems in heritage buildings with a Mediterranean climate to reduce energy consumption. Cabeza et al. [33] studied energy savings in historic buildings with different passive systems, showing savings ranging from 24% to 65%. These studies made it possible to assess the environmental threats and identify the vulnerability of historic buildings and their heritage elements to future climate change scenarios, to propose timely mitigation and conservation strategies according to different climates. Although the shift towards lower carbon fuels has gradually reduced the carbon intensity of the global economy recently, this background decarbonisation is far from sufficient to achieve the carbon reductions needed to stabilise the climate [12]. However, with the trend in energy consumption in buildings, the passive techniques approach has become relevant. In this respect, historic buildings have limitations in applying effective resilience measures. Due to decorative, heritage, etc. issues, it is impossible to apply energy conservation measures as in modern residential buildings. For these reasons, it is necessary to increase the effectiveness of applying resilient strategies in historic buildings.

Alternatively, religion is a feature of the integration of people because it allows, among other things, the creation of bonds of identity and a sense of belonging. Since 1895, the National Institute of Statistics and Geography has documented and classified religious practises in Mexico [34]. The Mexican population is traditionally mainly Catholic; however, during the 20th century, Catholicism has reduced its majority margin despite Christian proposals that differ from the Catholic tradition. Of the 126,014,024 people living in Mexico [35], more than 90% practice some religions. This practice is concentrated in the central region, with a temperate climate [36], where the benchmark case is located, with 96% of the population being religious [37].

In this study, a passive cooling system previously reported by Vázquez-Torres et al. [38] was analysed to determine, on a timeline spanning the entire 21st century, the effectiveness of passive cooling systems under future climate scenarios. The novelty lies in qualifying a recently developed passive cooling system, which consists of the implementation of a double skin with a mixed mode ventilation system in a historical religious building to determine the cooling necessities under two satisfaction comfort models and different occupancy levels.

The key objectives were: (1) to establish the current annual thermal performance of a religious building located in the historic centre of a Mexican city with a sub-humid temperate climate. (2) To evaluate under different climate scenarios RCPs with and without a passive cooling system, the thermal comfort at different occupancy levels. And (3), to determine the effectiveness of a novel passive cooling strategy applied in historic religious buildings that influence climate change. The social impact of this study adds to the solutions focused on the environmental health of buildings that seek to reduce emissions throughout the 21st century. And in narrowing the literature gap that currently exists in developing countries in relation to the prospective thermal performance of non-residential buildings constructed during the last century that provide elements to address climate change over this century.

2. Methods

This study analysed the performance of a Passive Cooling System (PCS) in the central region of Mexico. Fig. 1 illustrates schematically, the methodology developed in four phases. In the first phase, the thermal properties of the benchmark case were catalogued, the occupancy level and thermal performance were recorded through calibrated data loggers. The second phase consisted of defining the PCS and acquiring environmental data considering the current scenario (2022) and two future projections (2050 and 2100). The third phase was performed by elaborating and running the computational model through the Design Builder software [39] for the current scenario and future scenarios throughout the 21st century. Finally, the results were analysed by contrasting the internal temperature performance and the comfort hours through an adaptive comfort model with different levels of satisfaction (80% and 90%).

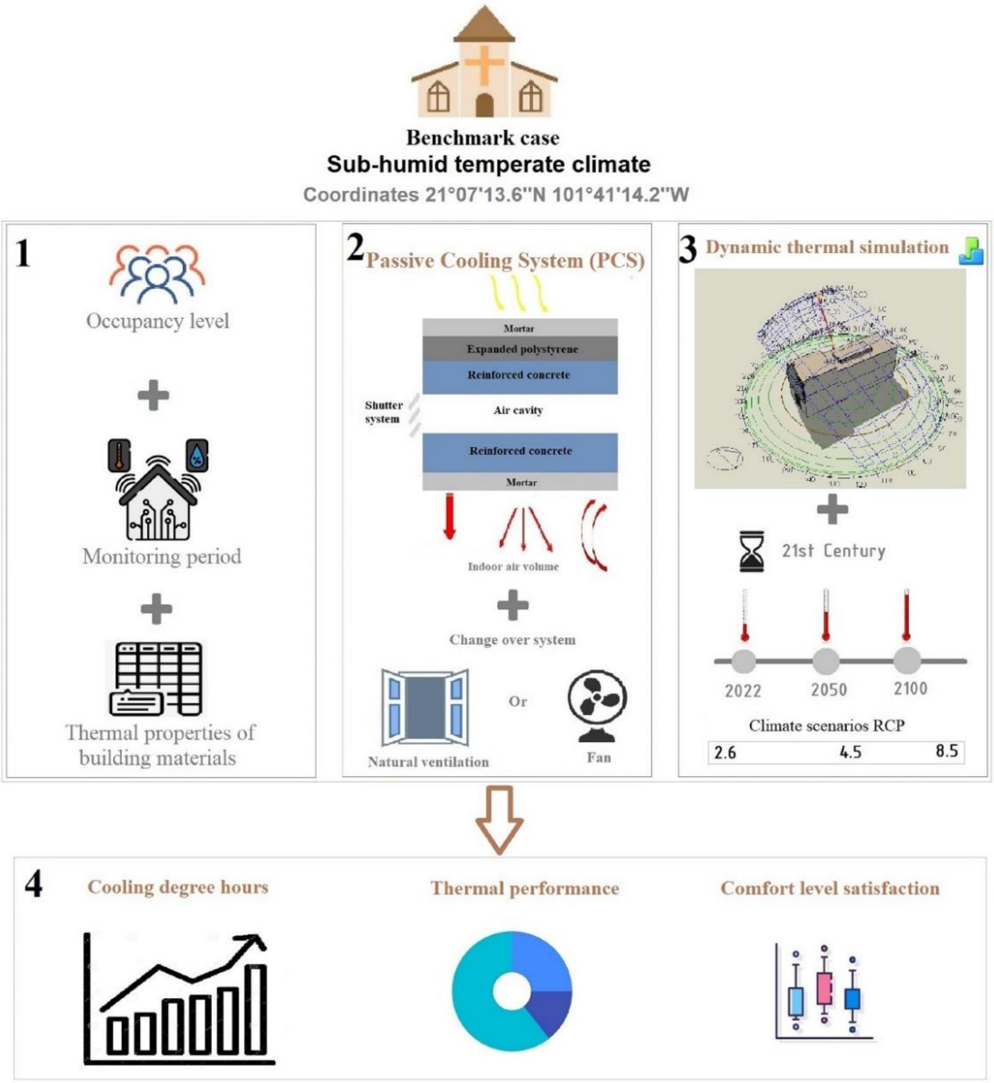


Fig. 1. Methodological outline for approaching the benchmark case.

2.1 Benchmark case and simulation characteristics

The benchmark case was built in the urban area called "Bajío" in the central Mexican region (coordinates 21°07'13.6 "N 101°41'14.2 "W). The city has a territorial extension of 1200 km², around 1.5 million inhabitants, a population density of 1250 inhabitants/km² and an average growth rate of 2.1% [40]. The climate classification developed by Köppen in 1884 is one of the most important and used in the world; however, it has limitations in describing the characteristics of the Mexican climates. Therefore, Mexican researchers García [36] and Gómez-Azpeitia [41] have developed methodologies based on Köppen findings to more accurately represent climatic conditions. The latter was based on ANSI-ASHRAE 55 [42] and 30-year measurements from the National Meteorological System [43]. According to Gómez-Azpeitia, the study city has a sub-humid temperate climate, prevailing winds from the southwest, dry bulb temperature of 21 °C, average monthly rainfall of 88.6 mm, relative humidity 63%, and wind speed of 9 m/s, during April to September (summer period).

The benchmark case is a historic building built in 1950; however, it is not considered a heritage building protected by the National Institute of Anthropology and History because it had been built before 1900. Due to geometric conditions, the primary internal heat gains come from solar radiation on the building roof slab. This resulted from a lack of professional advice, leading to self-construction techniques. The study building (Fig. 2) has an area of 78.4 m^2, the roof is made up of a slab system, the mezzanine is made of reinforced concrete, the walls are baked red brick, and the windows located on the first floor consist of 3 mm glass. One of the fundamental strategies for space cooling is ventilation control, which involves mixing gases within the space, or more formally, mixing air currents with different thermal properties. The building includes a concurrent ventilation system [44], which uses natural and mechanical ventilation (43-W power fan) during the occupancy hours shown in Table 1.

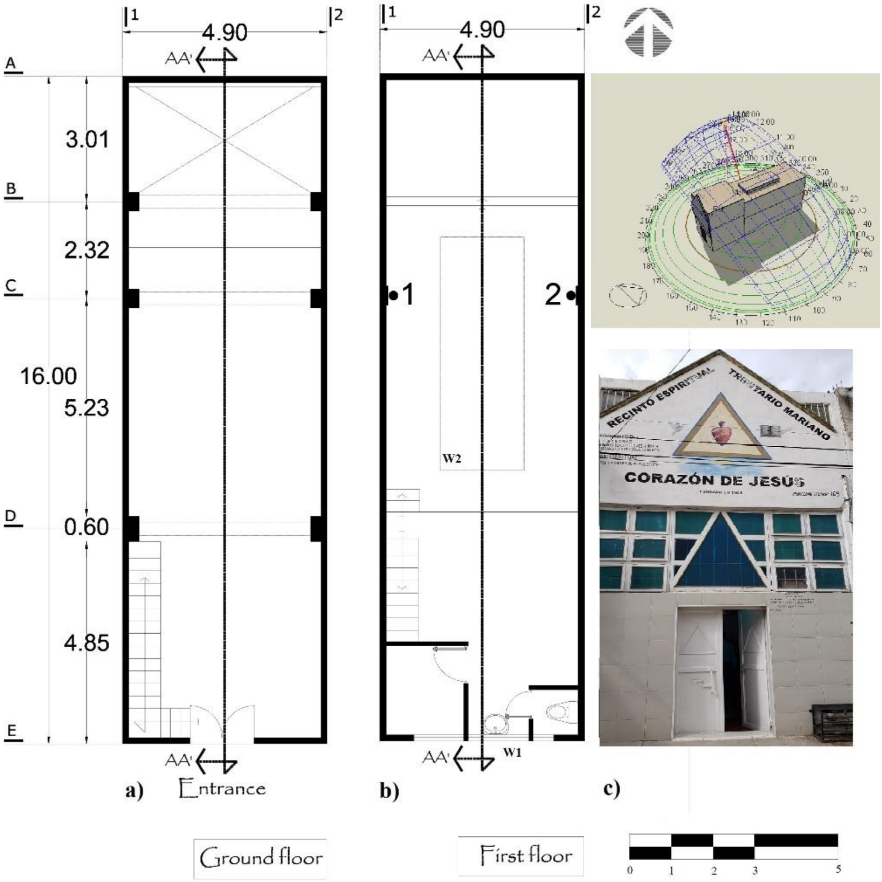


Fig. 2. Spatial delimitation of the benchmark case.

The building was visited throughout the year to observe the behaviour of the thermal sensation in different seasons. According to the National Meteorological System, May is the month with the highest temperatures historically [43], so data was taken for this representative month in 2021. With this information, the passive cooling technique was concentrated on the first floor to record the most significant thermal performance with Elitech data loggers model RC-51H, which had been previously calibrated, and were placed at a height of 1.7 m as recommended by the ASHRAE 55-2020 [42], as shown in Fig. 3.

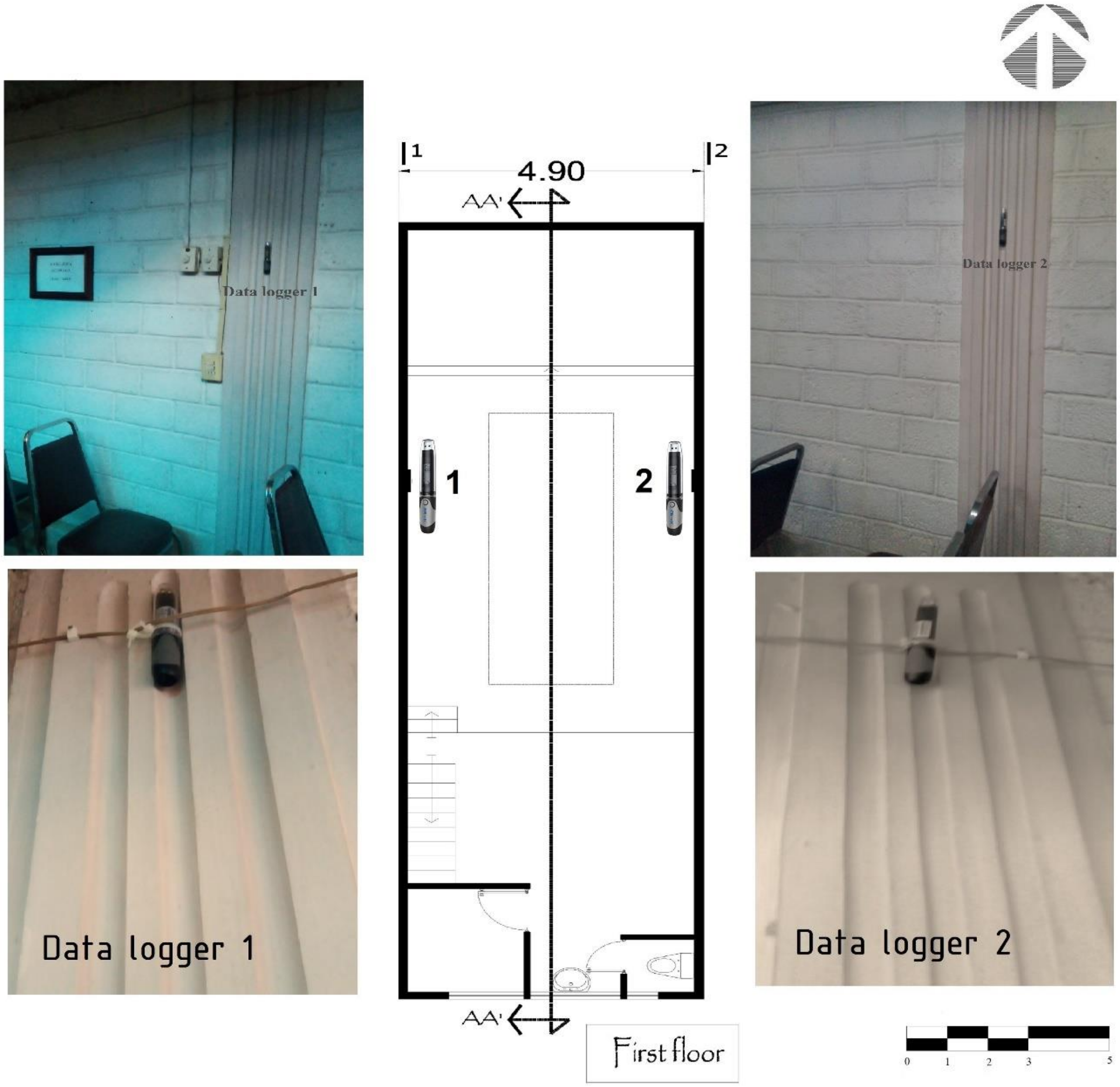


Fig. 3. Data logger's location on the first floor.

Occupancy levels of the religious precinct were collected with individual and group meditations. Table 1 presents the occupancy details, which were subsequently used in the Design-Builder simulations [45]. The metabolic rates measured in W/person stipulate the human heat produced through oxidation. An average value between men and women of 0.9 W/person was used in the simulation scenarios.

Table 1. Occupancy details used in the simulation process [38].

Occupancy level	Average occupancy	Density Persons/m^2	Metabolic rate W/persons	Occupancy hours
Zero (Saturday)	0	0	0	0
Medium (Tuesday)	33	0.4	29	16 to 19
Highest (Sunday)	88	1.1	79	9 to 12

The building has a low airtightness, so the thermal simulations were generated with a poor infiltration rate (0.7 ren/h) [46]. The occupants 'activities in the religious compound correspond to a template for sedentary activities without electronic devices, so the occupancy levels: zero, medium and upper, were set to determine the influence of the thermal performance by the envelope, and with the additional gains by human metabolism. The occupancy method corresponds to the people per floor area, in which the latent gains refer to the humidity due to perspiration and respiration as a function of indoor temperature and metabolic rate [47]. Fig. 4 shows the dry bulb temperature and relative humidity measurements in May 2021. Higher oscillation data is evident, contrasting with the meteorological variability of the area. A higher temperature oscillation was observed, due to the low airtightness in the building with respect to the outside conditions.

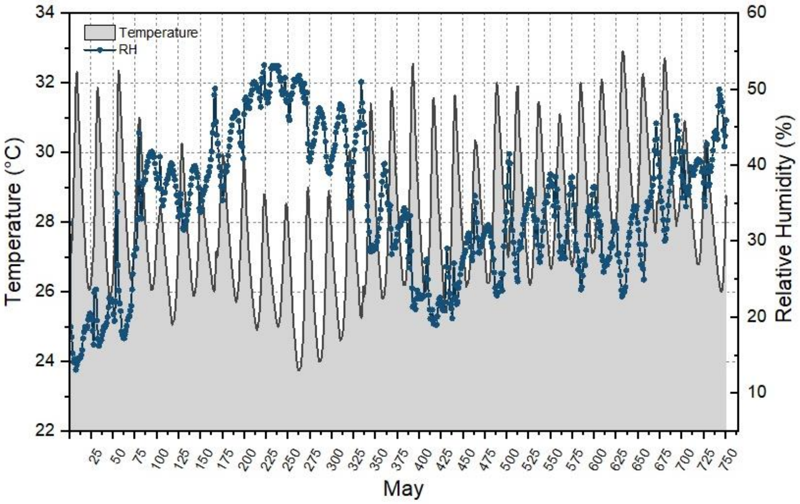


Fig. 4. Monitoring results in the representative month.

2.2 Meteorological database generation

The climatic data comprised the current year (2022) and two future projections (2050, 2100). Future projections consider climate change scenarios RCP and provide valuable data on radiative forcing components for integrated climate model analyses and assessments [50,51]. RCP climate models incorporate the carbon cycle and simulate the pattern of CO_2 fluxes that develop between the ocean and the atmosphere, as well as outgassing in the tropics and absorption in the mid- and high latitudes. These models include estimates of the simulated global terrestrial and oceanic carbon sinks during the latter part of the 20th century [30]. Three scenarios of RCP were chosen to observe the impact of climate change on the building thermal performance [50]:

- The RCP 2.6 scenario follows the peak and decline trend; it is considered a low-impact scenario because it considers a temperature increase range from 1 °C to 1.5 °C and a CO_2 concentration between 490 ppm and 530 ppm and a radiative forcing of 3 W/m^2 [27,53].
- The RCP 4.5 scenario considers a temperature increase between 1.5 °C and 2.4 °C, 580 ppm to 720 ppm of CO_2 , and radiative forcing of 4.5 W/m^2. It is, therefore, considered an intermediate scenario [3].
- The RCP 8.5 scenario tends towards an upward radiative forcing trajectory [27]. It considers a temperature increase between 3 °C and 4.8 °C, Concentration of CO_2 greater than 1000 ppm, and radiative forcing of 8.5 W/m^2. Therefore, it is considered a high-impact scenario [3].

2.3 Adaptive comfort model

The benchmark case meets the specifications of the ASHRAE Standard 55 comfort model, specified for buildings without HVAC systems and that comply with natural ventilation (empirically operated in this case). The selected model established an average outdoor temperature between 10 °C – 33.5 °C and a sedentary occupant activity between 1 – 1.3 [51]. The comfort temperature (T_{comf}) was quantified with Eq. 1 [52], and calculated from the average daily outdoor temperature (T_{out}) employing data from the National Meteorological System in the selected city [43]. It was determined to use the two satisfaction percentages proposed by the ASHRAE 55-2020 standard, 80% and 90% with a range of 7 °C and 5 °C respectively, for further analysis. Fig. 5 shows the comfort range with the average dry bulb temperature line resulting from the monitoring period [42].

$$\text{Tcomf} = 0.31\ \text{Tout} + 17.8 \qquad (1)$$

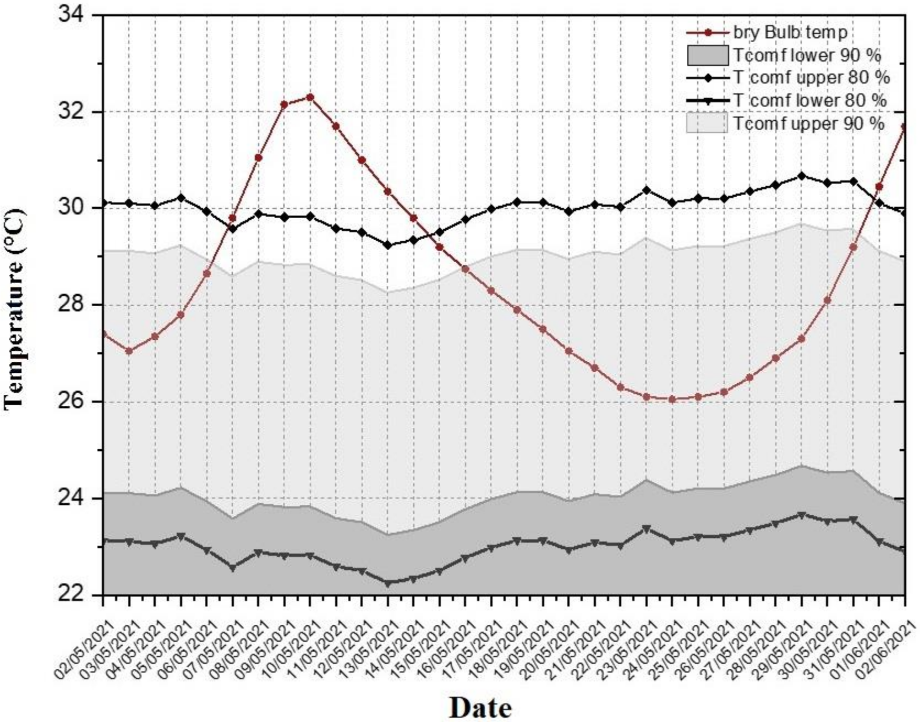


Fig. 5. Comfort range according to the benchmark case.

2.4 Passive cooling system (PCS)

A PCS was used to lower the temperature of the entire building and lose thermal energy (heat) or delay the energy exchange, specifically on the first floor, where heat is concentrated due to air stratification. The PCS integrates a change in the mixed-mode ventilation system. A concurrent system is now used, and a "change-over" system is proposed (the building switches between natural and mechanical ventilation hourly) [53]. A timetable for the use of mechanical ventilation was established as follows: Tuesdays from 16:00 to 19:00 and Sundays from 9:00 to 12:00, during the summer period. The mechanical cooling system had a high level of airtightness in the enclosure to optimise the ventilation system. The lower occupancy levels were controlled by natural ventilation, especially on the first level where high temperatures are concentrated.

Additionally, a double roof skin and an air cavity were proposed, as shown in Fig. 6, where the layer thickness is shown in metres. The thermal process of the PCS is as follows: sub-humid air enters at a high temperature due to the incident solar radiation; the airflow passes over the PCS. As the air with low moisture content and high temperature passes through, the passive system generates a barrier that slows the temperature exchange with the indoor air volume. Indoors, the air experiences thermal conduction, radiant heat, and convection. The shutter system also provides an additional outlet for the warm air accumulated on the first floor (see Fig. 6). At the process outlet, the air would have a lower temperature, which would decrease the interior thermal sensation when the openings of the interior space are open. These two principles govern the PCS process.

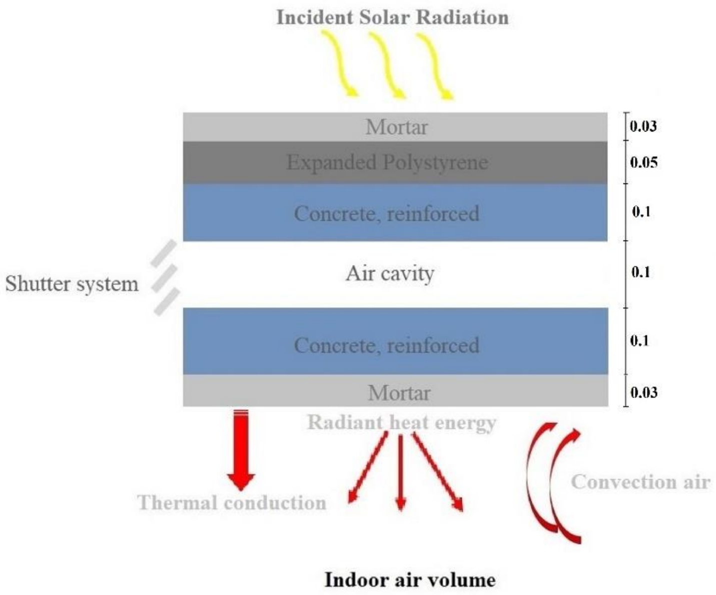


Fig. 6. Schematic design of the PCS.

The low conductivity of the expanded polystyrene and the PCS thermal mass creates a thermal envelope that insulates the interior space from all climatic factors, such as solar radiation. It delays heat exchange to the interior during occupied hours, improving the user's thermal comfort. The thermal properties of the construction system used in the calculation of conductive heat gain are shown in Table 2, based on [43–45].

Table 2. Thermal properties of the construction materials used in the study.

Material	**Thickness (m)**	**ρ Kg/m^3**	**Ce J/Kg*K**	**λ W/m*K**	**U W/m^2*K**
Mortar	0.03	2800	896	0.88	-
Expanded polystyrene	0.05	15	1400	0.04	0.6
Concrete	0.1	2400	900	2.15	0.556
Air cavity	0.1	1000	1000	0.3	-

2.4.1. Validation model

The computational results were validated for their execution in different scenarios through a statistical criterion of the data from the simulations or projections (P) and data collected (O) as shown in Fig. 7.

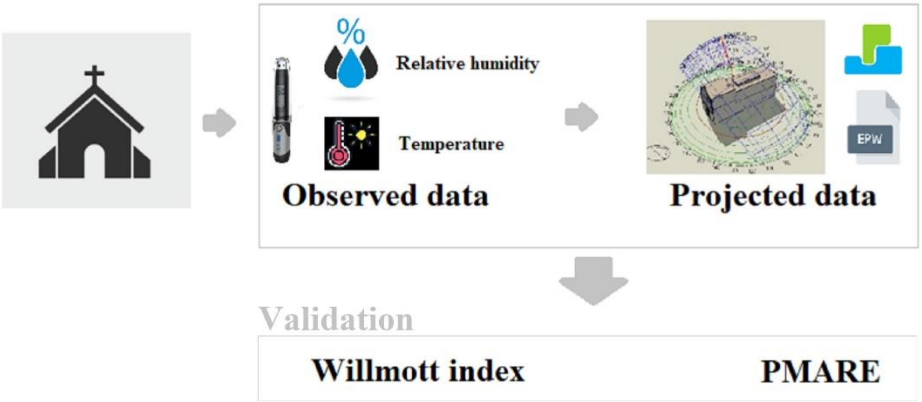


Fig. 7. Schematic view of the validation process

Ali et al. [57] proposed the index called Percentage of mean relative absolute error (PMARE) presented in Eq. 2; in their study, Ali et al. evaluated common validation models, such as the mean bias or mean error (ME), the mean square error (RMSE) and the Willmott's index (Eq. 3).

$$\text{PMARE}\ (\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{Abs(O_i-P_i)}{O_i} \qquad 2$$

Where:
$O_i = \text{Observed dry} - \text{bulb temperature}$
$P_i = \text{Simulated dry} - \text{bulb temperature}$
Abs= Absolute value

The PMARE has been used in studies to evaluate the efficiency of different models such as the developed by Zhao et al. [58]; and establishes evaluation criteria from dissatisfaction (> 25%), to excellence (0 % – 5%). This study used the PMARE [57] and the Willmott agreement index [59],. The Willmott's index continues to be one of the most widely used validation models by the scientific community in different disciplines, for example, in the research developed by Hao et al. [60].

$$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}[O'_i + P'_i]^2} \qquad 3$$

Where: $O'_i = |O_i - \bar{P}|$, $P'_i = |P_i - \bar{P}|$, O_i is the observed value and P_i is the simulated value and $\bar{P}$ is the simulated mean.

Table 3 shows the pertinent considerations for calculating these statistical methods; likewise, an adequate correlation of the information is observed considering the execution of these models with 751 data pairs.

Table 3. Error values obtained from the pairwise review of the validation models.

Data logger	**Willmott** [61]	**PMARE** [57]
Elitech RC-51H	0.6	4.6 %

2.5 Mexican Standard validation

In 2001, the Mexican official standard NOM-008-ENER-2001 was established [62] for energy efficiency in the building envelope, to regulate and improve thermal design, and to reduce cooling needs in all climates in the country. For the application of this standard, buildings whose primary use is industrial or residential, were excluded. From this standard, the total heat gain determined by Eq. 4 was quantified, where Q_c refers to the heat gain by conduction and Q_r refers to the heat gain by radiation. A glazed area of 24% was considered in the main façade wall (south facing).

$$Q_{tot} = Q_c + Q_r \qquad 4$$

The radiation heat transfer mechanism, which occurs mainly through the windows, was calculated using the following equation:

$$Q_r = \mathrm{A} * \mathrm{CS} * \mathrm{FG} \quad 5$$

Where: A equals the area in m^2, CS refers to the shading coefficient and FG indicates the solar gain factor in W/m^2. To calculate the conduction heat gains, Eq. 6 (Fourier Equation) was applied, which includes conductance parameters or U-value (given by the conductivity divided by the material thickness), the building system area, and the difference between outdoor and indoor temperatures.

$$Q_c = [\mathrm{U} * \mathrm{A} * (T_{out} - T_{in})] \quad 6$$

Where: U (W/m^2 °C) refers to the conductance or heat transfer coefficient, A is equal to the area in m, T_{out} indicates the outdoor temperature and T_{in} represents the indoor temperature measured in °C. The references for the equations shown in this section can be found in NOM-008-ENER-2001 [62]. The PCS system, evaluated with Mexican regulations, establishes a reduction in heat gain of 70% to the reference case, resulting in a better energy consumption performance.

3. Results and discussion

Fig. 8 presented thermal simulations with the climate scenarios RCPs 2.6, 4.5, and 8.5 to observe the thermal performance of the benchmark case with and without the proposed PCS. Medium and upper refer to the occupancy level with PCS; data with zero occupancies were not included to prioritise the highest occupancy levels. In all three scenarios, the highest operative temperature corresponded to the models without the PCS in different proportions, and conversely, the lowest temperatures corresponded to the models with the PCS, which even presented heating needs according to the comfort model. The Climatological data measured for 30 years indicated that the month with the highest temperature in the current scenario is May. Fig. 7 shows that RCPs 2.6 and 4.5 extend this trend between months 4 and 6, while RCP 8.5 also includes July. Between RCP 2.6 and 4.5, a temperature increase of 1 degree reached 35 °C, and RCP 8.5 exceeded 37 °C.

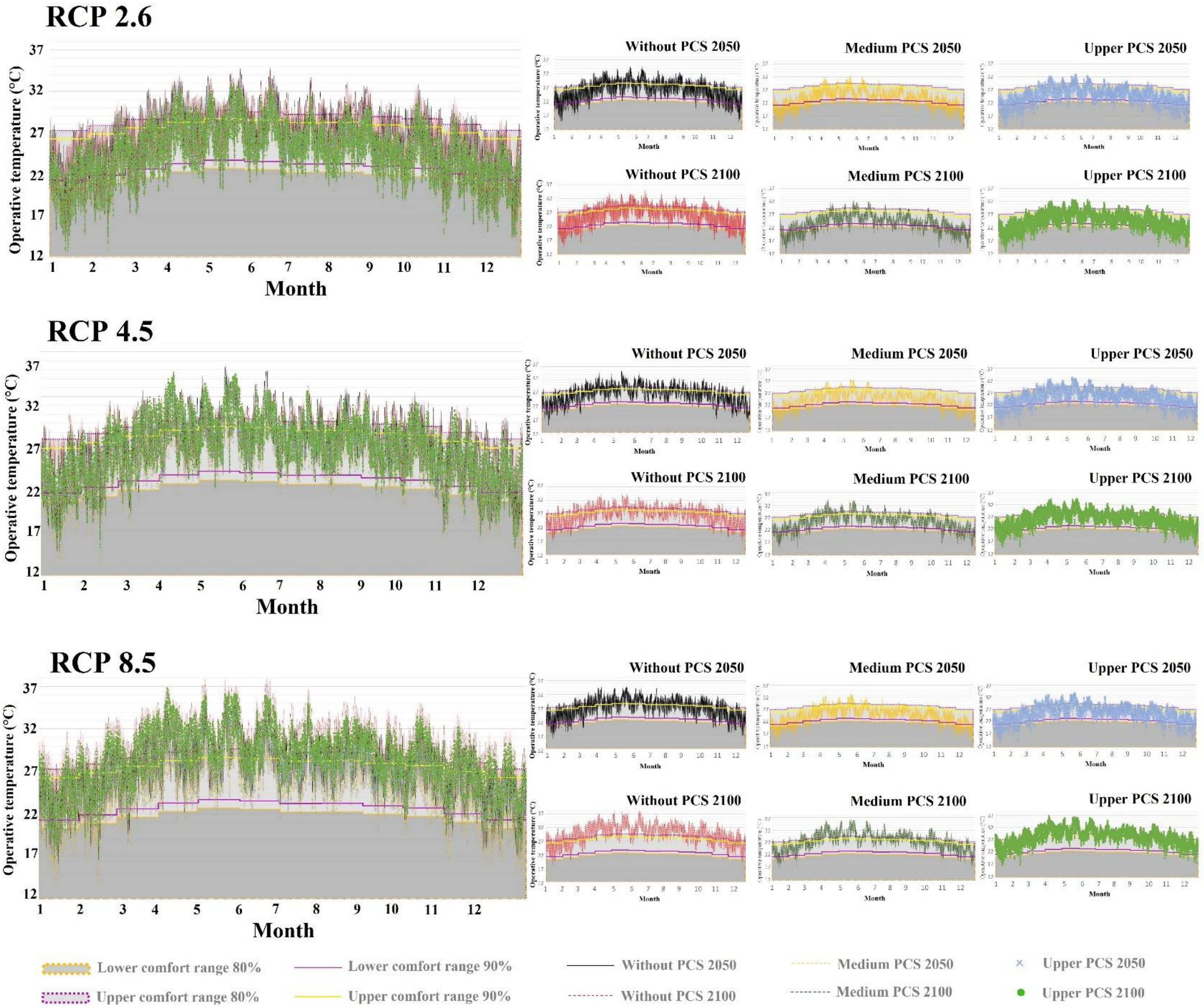


Fig. 8. Operative temperature performance throughout the 21st century.

The degree hours are based on an empirical or theoretical observation of heat gains and losses in Celsius, with respect to the comfort temperature hourly [63]. To analyse the annual results of the future scenarios, Fig. 9 shows the cooling degree hours (CDH) with the comfort model for 80% and 90% satisfaction levels. The PCS showed a high efficiency against climate change, with quantifications less than half of the results observed for the models without the PCS. RCPs 2.6 and 4.5 showed directly proportional increases in almost all cases, while RCP 8.5 showed a pronounced increase in all cases.

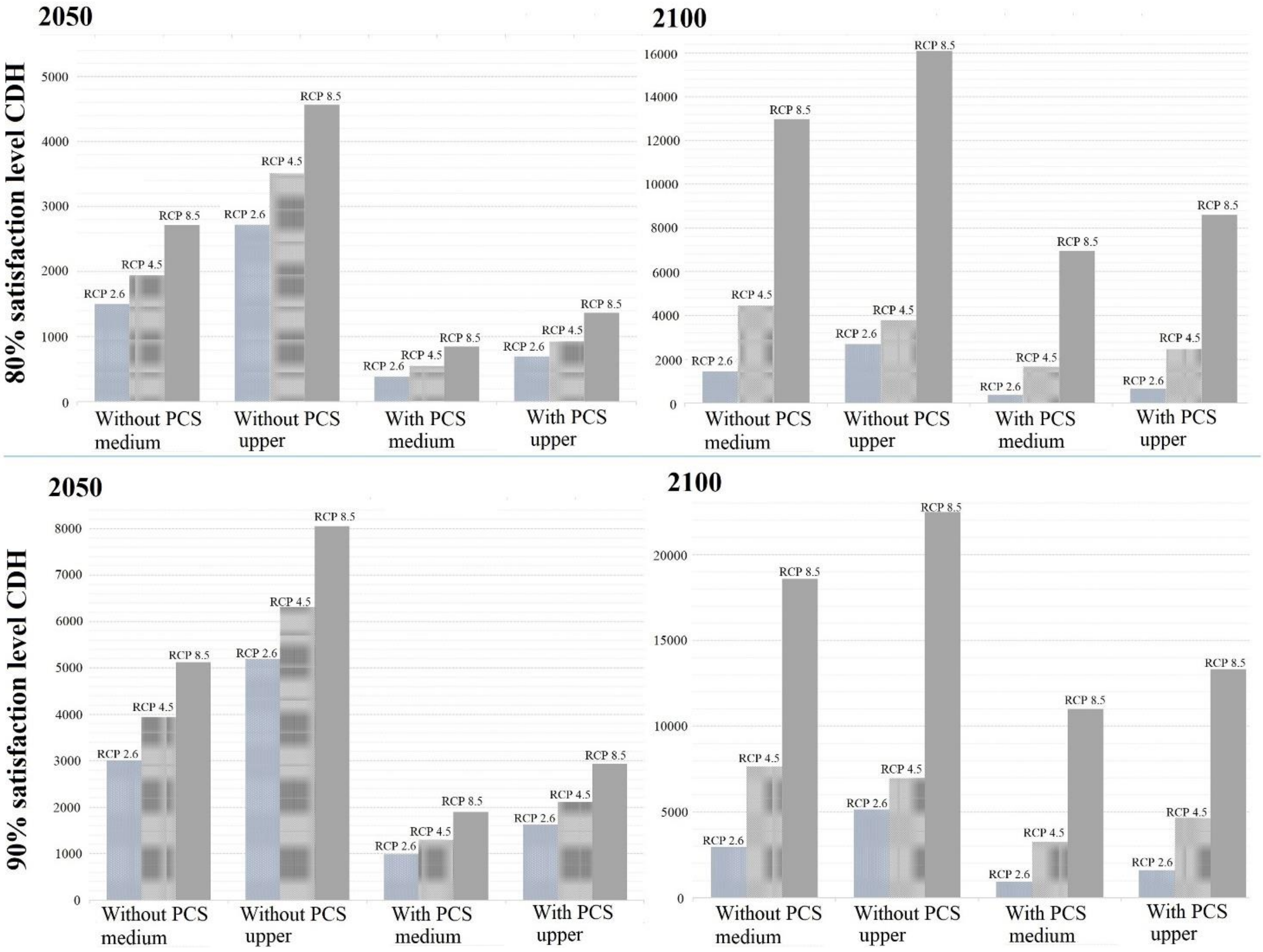


Fig. 9. CDH needs prospective for 2050 and 2100 scenarios.

The upper occupancy level showed different CDH according to each scenario and satisfaction level, as shown in Fig. 10, where the inner circle corresponds to the CDH in percentage with the PCS, and the outer circle corresponds to the CDH in percentage without the PCS. In the upper occupancy with a satisfaction level of 90%, cases with the PCS had 47% less CDH than those without the PCS. While at the same occupancy level with a satisfaction level of 80%, cases with PCS had 43% less CDH than cases without PCS. In all cases, RCP 8.5 by 2100 would increase the CDH by 33%-55% compared to the current scenario. The data for the highest occupancy level in all scenarios refer to the effectiveness of passive systems applied to a building typology and temperate climate that have been uncommon studied.

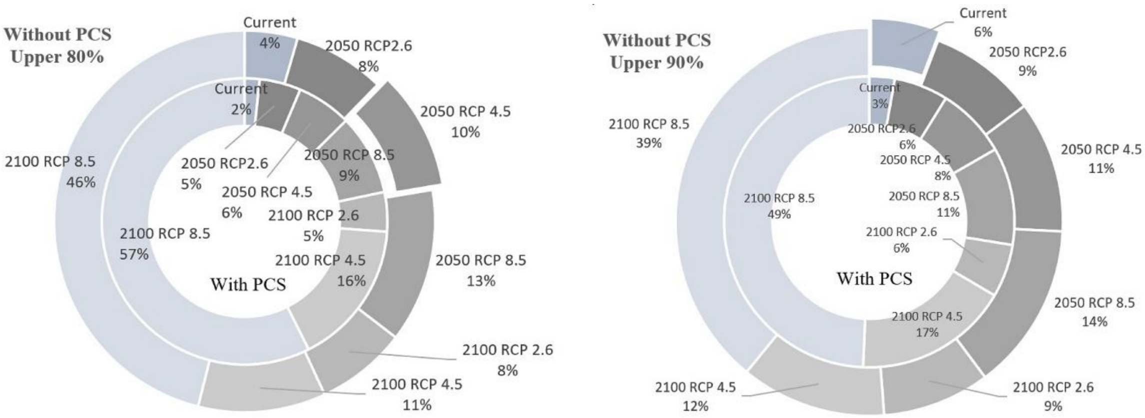


Fig. 10. CDH prospective for upper occupancy level.

Fig. 11 analysed the CDH variability according to the satisfaction level. The current scenario with upper occupancy level was compared with the future scenarios. In the current scenario (Fig. 10a), a difference in the maximum value of 1.2 CDH was found between cases with and without PCS in the current scenario. The projection to 2050 shows a linear behaviour between the different scenarios using the PCS, where the average value remains almost constant at 0.2 and the maximum value increases by 0.7. A higher variability between quartiles is also shown in the pessimist scenario RCP 8.5 in 2100. The 2100 Projection shows outliers with higher amplitude in RCP 8.5 and a difference of 2.5 CDH between the case without PCS in the current scenario and the scenario RCP 8.5 with PCS. In Fig. 10b, starting from zero, outliers corresponded to the difference between the two satisfaction levels as the level of satisfaction increased. In the current scenario, there is a difference of 1.26 CDH for the maximum value in cases with and without the PCS. The variability between quartiles was most noticeable in the prospective RCP 8.5 in 2100. In 2100, the case with the PCS and RCP 8.5, there is an increase of 1 CDH compared to the current scenario without the PCS. These results quantitatively show the effectiveness of the passive system proposed over the 21st century.

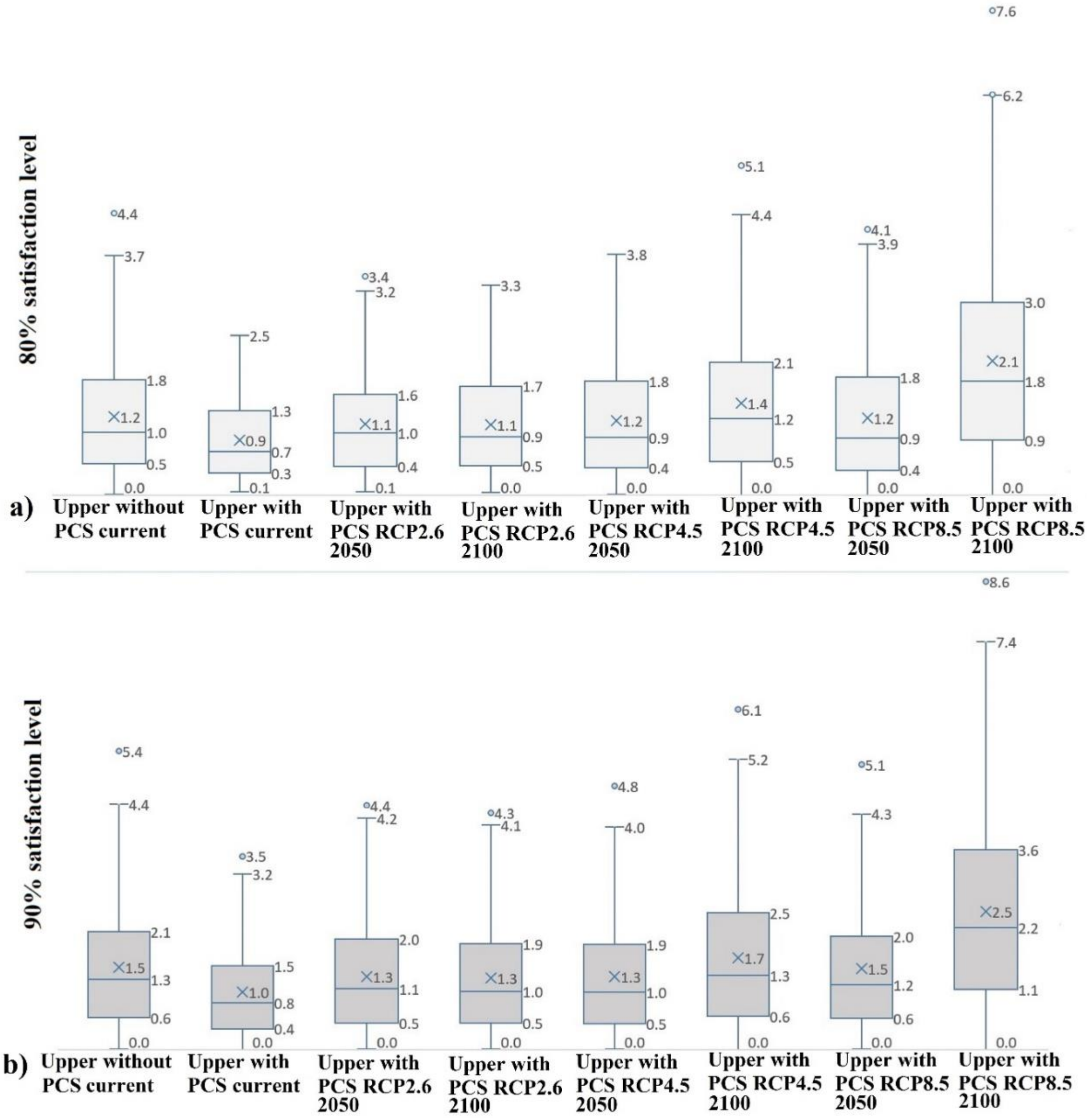


Fig. 11. Analysis of data variability in future scenarios with upper occupancy level.

To observe the thermal performance of the proposed passive system in detail, the results for May, the month with the highest temperature recorded in the current scenario, were added. Fig. 12 presents the results of the RCP 2.6 scenario for 2050 and 2100.

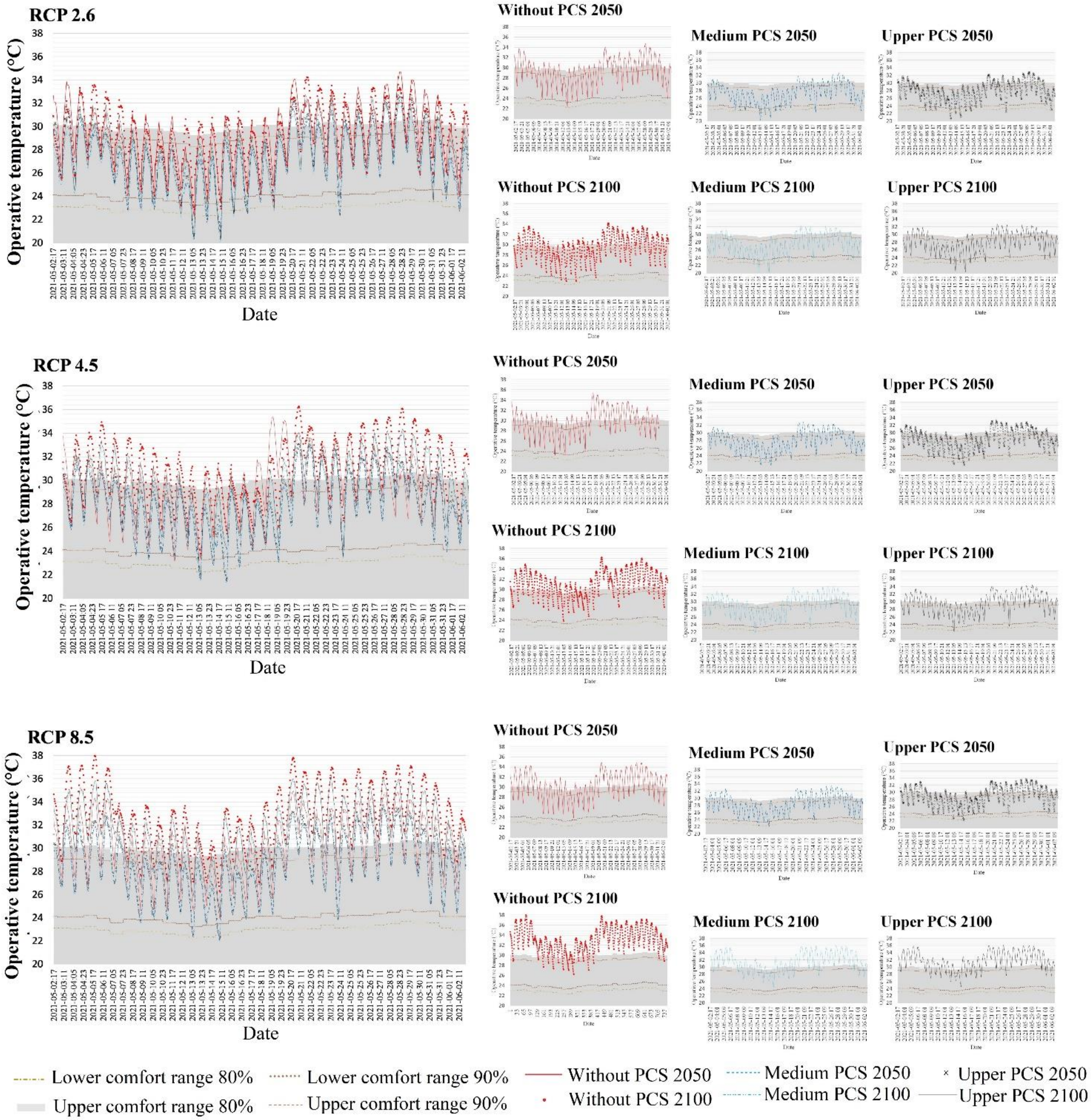


Fig. 12. Operative temperature performance in May with future scenarios.

When comparing the results of future climate simulations with measured data in the building, it was observed that the temperature threshold without the PCS increased, at the beginning and end of the month studied, by at least 2 °C. Note that with the PCS used, these data do not reach the expected increase in the scenario considered as "optimistic", which demonstrates a climate change mitigation capacity. In the RCP 4.5 scenario, an increase in operative temperature of more than 3 °C was observed. The model without PCS in the 2100 climate scenario showed more than 1 °C almost the entire period, representing an increase in cooling needs. At both occupancy levels, it was observed that with the PCS, there were smaller oscillations and an increase of less than the 2 °C expected in this scenario. Compact oscillations allow for greater control of indoor thermal conditions with passive strategies, such as the level of airtightness in the building. All models in RCP 8.5, with and without PCS, presented an increase in operative temperature; however, it is observed that under this scenario, PCS presents a resilient response to the pessimistic climate change in RCP 8.5. Using PCS presents an innovative opportunity that increases the capacity to tolerate abrupt outdoor climate conditions. The most negligible thermal performance oscillations occurred in the PCS cases, even in the most "pessimistic" scenario. To analyse the decarbonisation capacity of the historic religious building in the warmest month, the CDH was quantified with and without the PCS, in the current scenario at two different occupancy levels, and under the satisfaction levels (80% and 90%) as shown in Fig. 13.

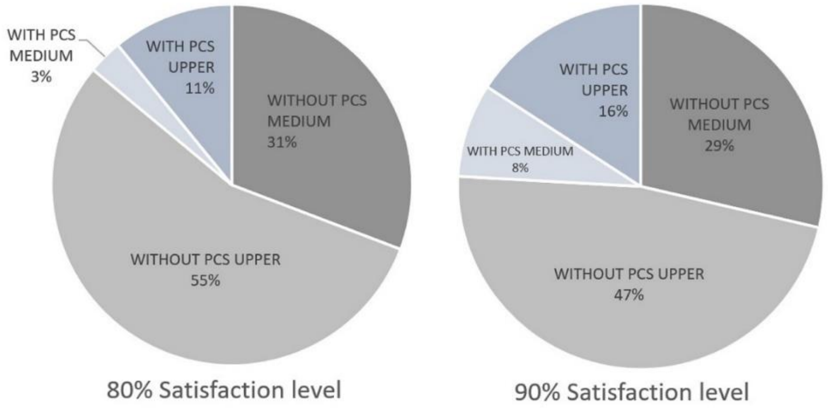
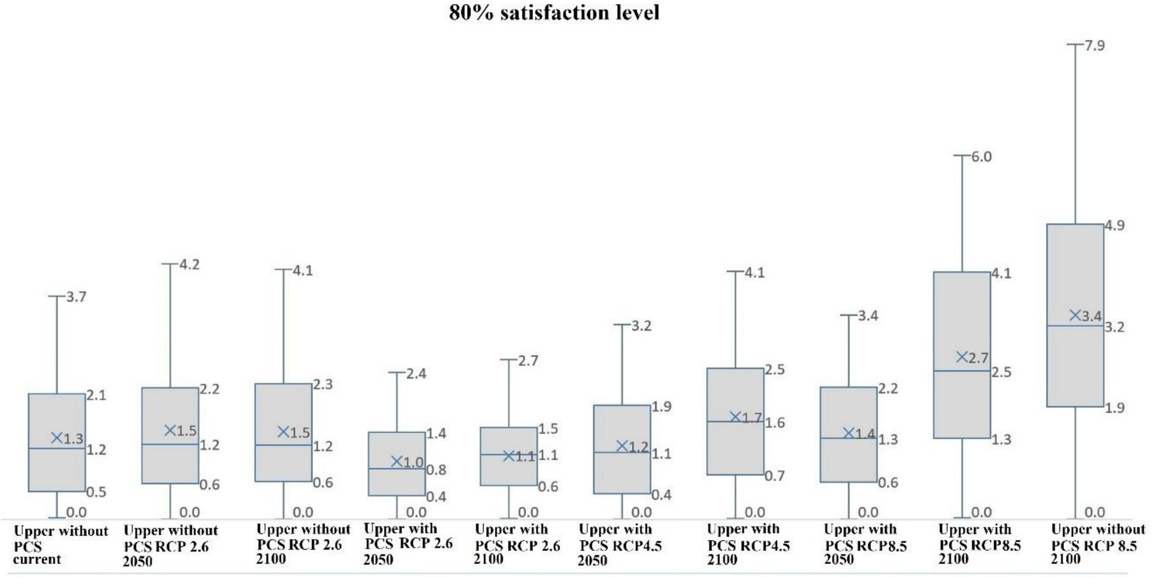


Fig. 13. CDH needs under two levels of satisfaction in the current scenario.

In both cases, the use of PCS showed a significant decrease in cooling needs for medium and higher occupancy levels, evidencing the efficiency of using passive systems in temperate climates and their ability to provide comfort versus the residual use of active systems. The decrease in the use of active systems is directly related to a decrease in the high levels of carbon released by active cooling systems.

The representative month with 80% satisfaction (Fig. 14) showed a difference of 4.2 CDH in the maximum value without the PCS between the current and RCP 8.5 2100 scenarios. Using the PCS would imply a decrease of 1.9 CDH in the maximum value at the end of the 21st century under the RCP 8.5 scenario. The average value without the PCS in the current scenario doubles in the worst scenario with the PCS (RCP 8.5) by 2100, and the model without the PCS in the same scenario increases by 2.1 CDH. Increasing the level of satisfaction to 90%, a proportional increase of approximately 1 CDH was observed in all scenarios concerning 80% satisfaction. The data variability with and without the PCS is concentrated between quartiles 2 and 3, in RCP 8.5 at the end of the 21st century. The difference of almost 2 CDH between the maximum values with and without the PCS in the pessimistic scenario implies a lower energy use to achieve thermal comfort for 90% of the occupants.



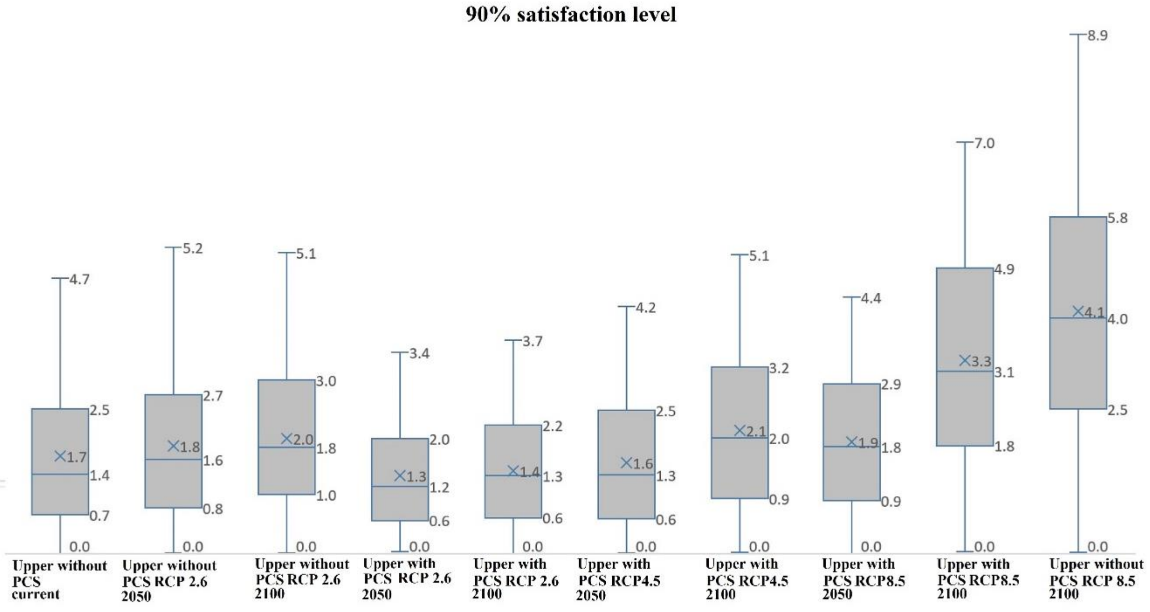


Fig. 14. Data variability in the representative month over the 21st century.

Finally, with the upper occupancy level and the most unfavourable scenario RCP 8.5 for 2100, the performance of outdoor vs. indoor temperature with and without the PCS was analysed (Fig. 15). Based on 30 years of observed data (1981-2010) [44], simulated data using the PCS showed a reduction in temperature during the warm months and an increase in temperature during the cold months, acting as an effective passive system in temperate climates in the current scenario. Even in the most unfavourable scenario (RCP 8.5 in 2100), the use of the PCS showed a year-round temperature reduction of 1.1 °C and 1.9 °C. There is a minimal difference in the expected temperature performance for 2100, and the building without PCS stands out.

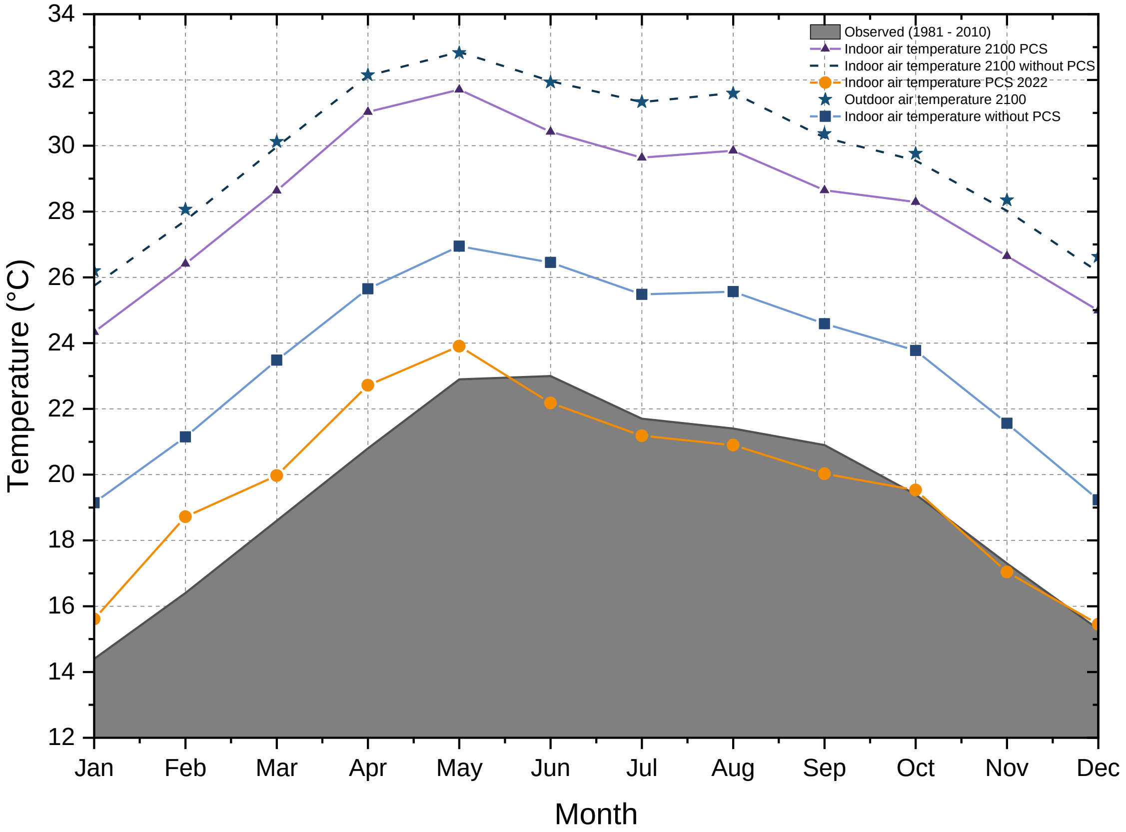


Fig. 15. Comparative analysis of air temperature under the different scenarios studied.

In the best scenario, an increase in the maximum temperature is expected to affect the health of the building and the users. This will generate a higher energy demand to achieve comfort levels. The expected increase in temperature could impact comfort models throughout the 21st century because it depends on variables such as outside temperature, thermal sensation, among others.

In Mexico, there is an effort to define adequate public policies to guarantee environmental protection, through regulations such as NMX-C-460-ONNCCE-2009 [64] or NOM-020-

ENER-2011 [54], focused on insulation and energy efficiency for envelopes only in the residential sector. National strategic programmes include lines of research concentrated on community health and the impacts of climate change, air pollution, vulnerability, adaptation and resilience. Through the support of national research projects, the aim is to increase knowledge and emission mitigation strategies in the short, medium and long term related to air quality and climate change, among others. These projects seek to influence social and political transformation to achieve a change in the development of Mexican cities towards reducing inequalities, increasing resilience, adapting to climate change and carbon neutrality. The findings of this study reduce uncertainty in generating effective strategies and provide a reference to strengthen public policies and their linkage to policy makers or academics interested in climate change adaptation and mitigation and carbon neutrality in all sectors. However, it is important to document climate change threats to historic buildings and their impacts with different conservation methodologies. Such as the one developed by Wang et al. [65] who zoned heritage risks due to climate change, considering variables such as materials and age. The climate change assessment developed by Bienvenido-Huertas et al. [31] allowed the quantification of the performance index in different scenarios, to established zoning recommendations in hot climates and recommended the quantification of cooling strategies for the resilience of heritage buildings. The findings of this study document the influence of climate change on the heritage environment and its impacts. Severity trends of future scenarios were presented and the effectiveness of using passive systems in historic religious buildings with different occupancy levels, and temperate climate, with residual use of active systems, was quantitatively determined.

4. Conclusions

This study conducted measurements on a historic religious building under the current scenario to observe the thermal performance. A PCS was analysed, and the results were compared under three RCP climate scenarios (2.6, 4.5, and 8.5) in the 21st century to observe its climate change mitigation capacity in a sub-humid temperate climate. To achieve the main objective, a novel methodology based on experimental and numerical analysis of historic buildings was determined, which can be used as a reference for experimental and numerical studies aiming at net-zero energy/emission buildings for sustainable development. The following key results determined the effectiveness of the proposed PCS:

- Lack of information on the health of buildings and users prevails, despite an abrupt change in temperature [5], and its possible repercussions faced with global decarbonisation efforts in the building sector.
- May is the month with the highest temperatures, the use of the PCS represented a decrease of up to 2 °C in the current scenario, while projections for 2100 showed a decrease in temperature between 1 °C and 2 °C when using the PCS. The PCS does not diminish the existence of a temperature increase challenge; however, it significantly reduces the phenomenon to be addressed, and above all, this study gives an opportunity to take timely mitigation measures.
- A greater oscillation in temperature performance was also observed in the scenarios for 2100, as well as greater variability of data in quartile 3 of the data distributions. This could also influence an increase in the thermal sensation.

- Climate projections and their correlation with temperature increase provide mitigation opportunities to address climate change from two perspectives: maintaining comfort and securing the energy resources needed. The most unfavourable future scenario, RCP 8.5 for 2100 with the highest occupancy level, showed a temperature reduction between 1.4 °C and 1.9 °C using PCS.
- In the current scenario, the determined PCS showed an effective reduction of heat gains measured in watts by radiation and conduction by 70%. The results contribute to the consolidation of national regulations on the energy efficiency of buildings. And it generates an opportunity for developing policies applied to typologies that have not been studied from this perspective.

Due to the implications for human and environmental health, scientific advances on climate change in the building sector are one of the central issues in Mexico's strategic plans. The findings showed the effectiveness of suitable passive systems considering the climate and different levels of satisfaction and occupancy of typologies in Mexican historic centres. These results lead to the generation of effective passive strategies for national and international strategic issues. Furthermore, they can be a reference for generating policies on energy efficiency, climate change mitigation, and human and environmental health. The change in the mixed ventilation system showed an improvement in the thermal sensation of the users; however, a more in-depth study on ventilation systems in historic buildings involving social perception is needed. To increase the areas of opportunity, it is proposed to extend the case studies to 19th-century heritage buildings and a further analysis of the environmental quality, to rise the impact of existing buildings with lower emissions towards sustainable development.

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